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CONTENTS

NOTICES

A QUANTITATIVE STUDY OF INSTRUMENT APPROACH — J. F. W. MERCER

THE DETERMINATION OF TURBULENT SKIN FRICTION BY MEANS OF PITOT TUBES — J. H. PRESTON

THE ANALYSIS OF SHEAR DISTRIBUTION FOR MULTI-CELL BEAMS IN FLEXURE BY MEANS OF SUCCESSIVE NUMERICAL APPROXIMATIONS — DEREK R. SAMSON

THE FIFTIETH ANNIVERSARY OF POWERED CONTROLLED FLIGHT DINNER

TECHNICAL NOTES — L. G. WHITEHEAD : L. A. MCQUILLIN; F. G. IRVING : R. A. SAUNDERS; C. G. SAUNDERS : F. W. THORNE

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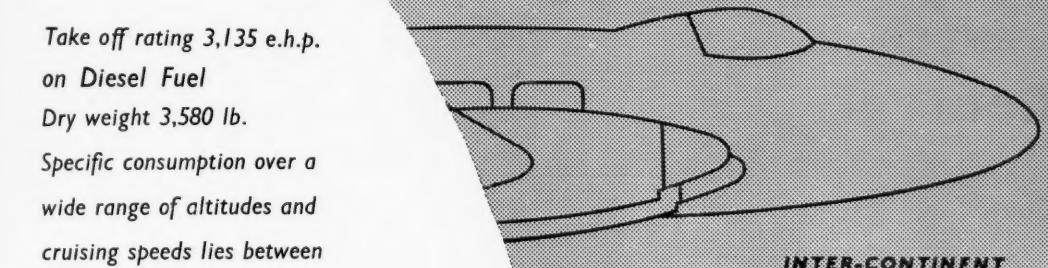
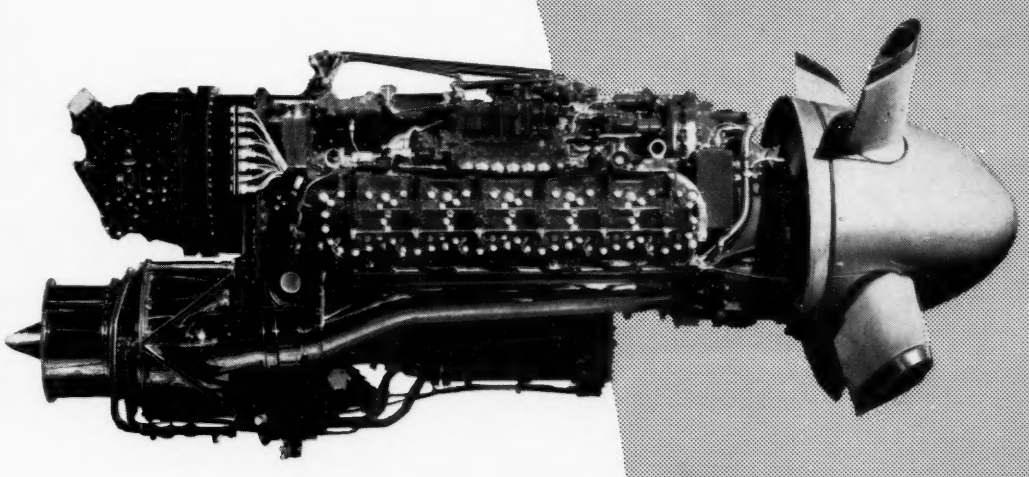


INTER-CONTINENT



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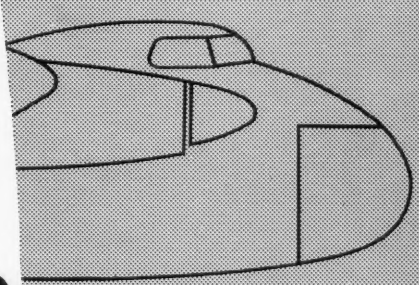

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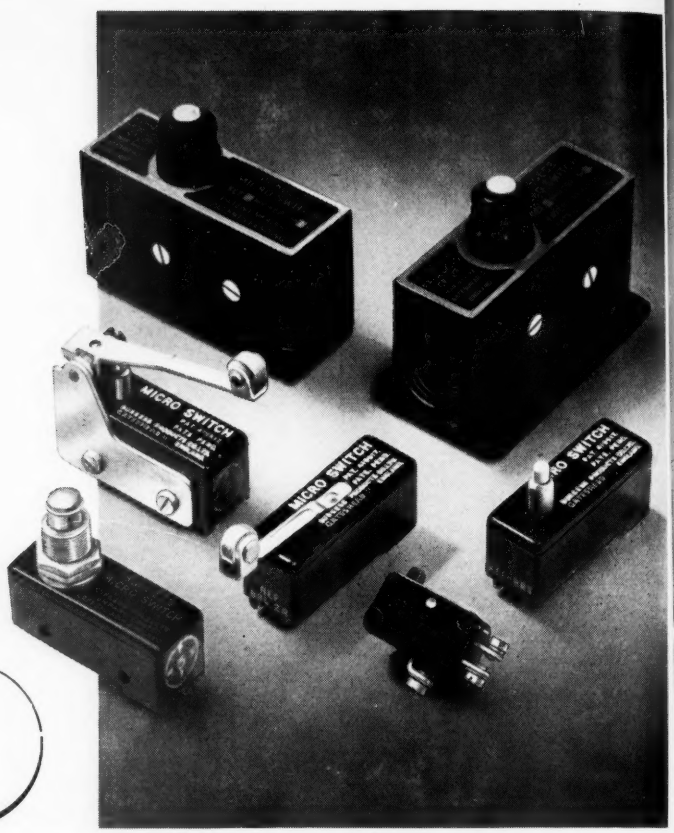

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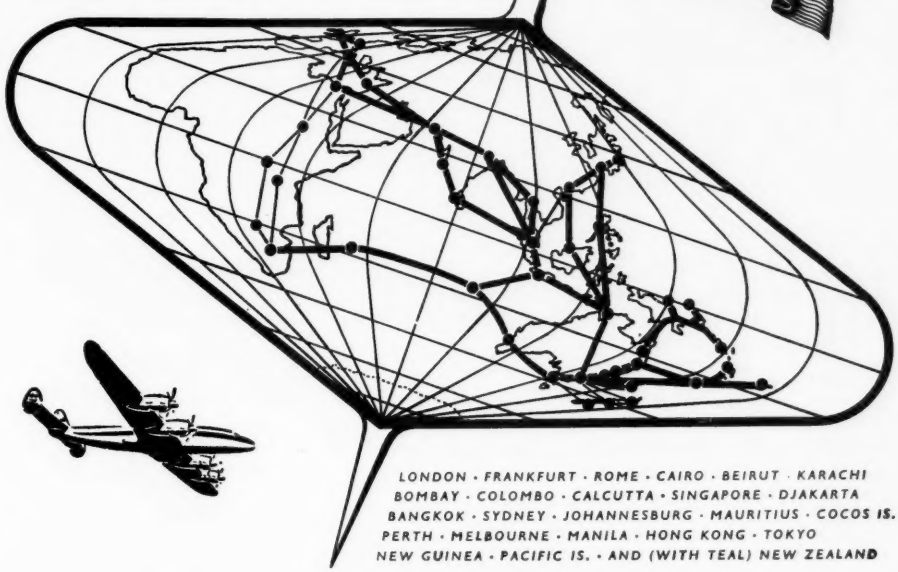

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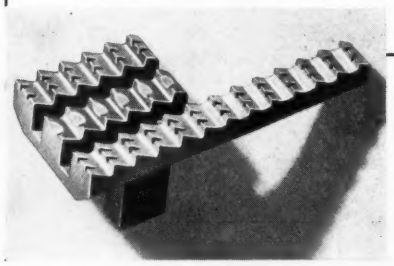
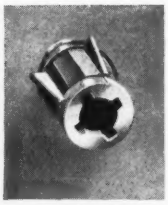
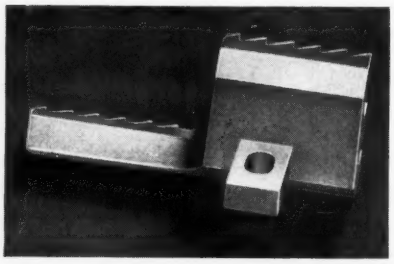
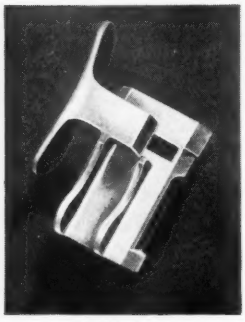


Two views of a feed mechanism in a high chrome molybdenum vanadium tool steel.

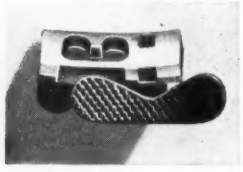


Coupling Hub in Cr-Mo-Va tool steel.





Two views of a helmet clip in stainless steel.



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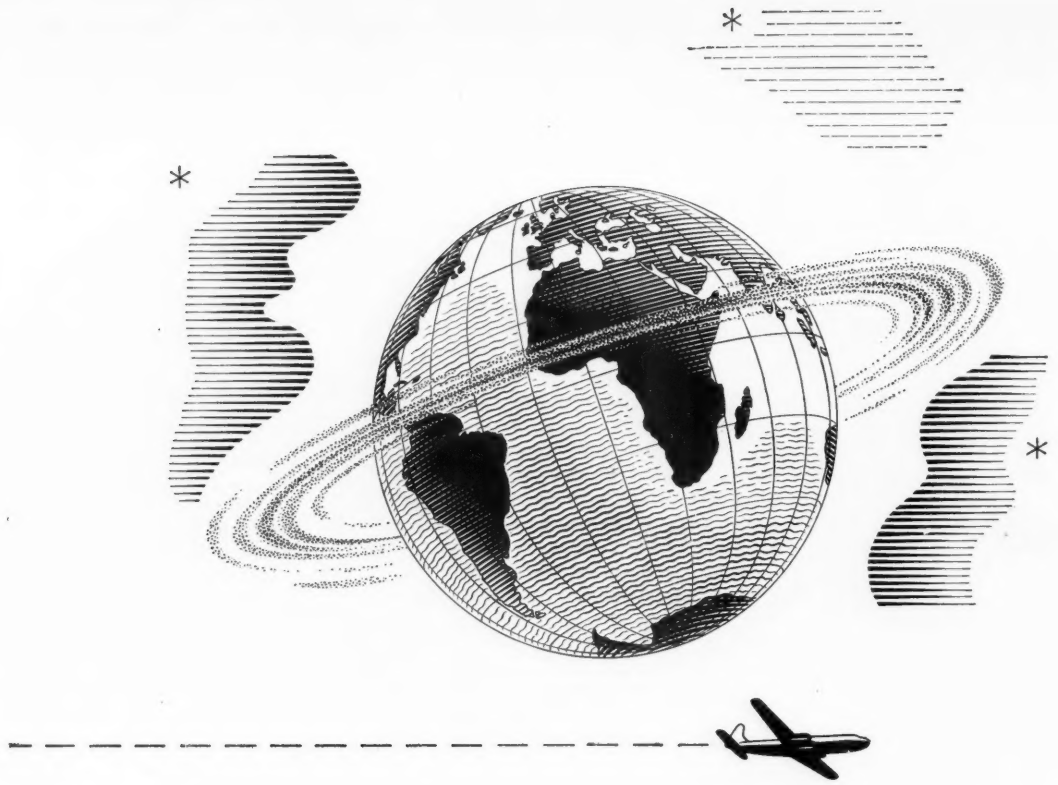

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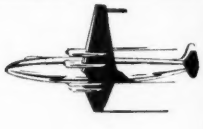

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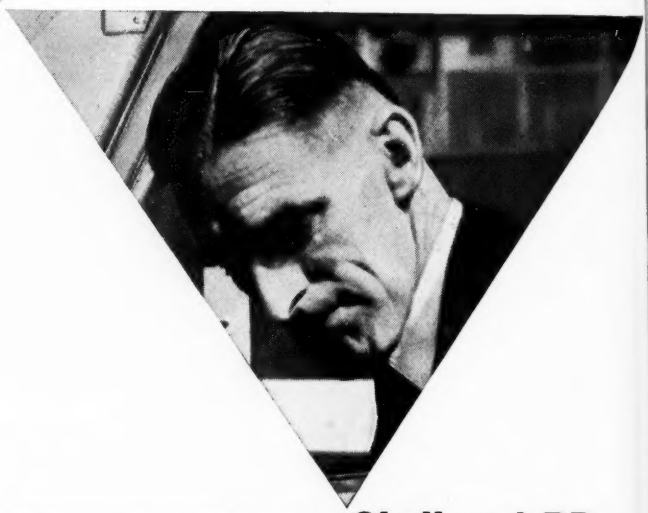

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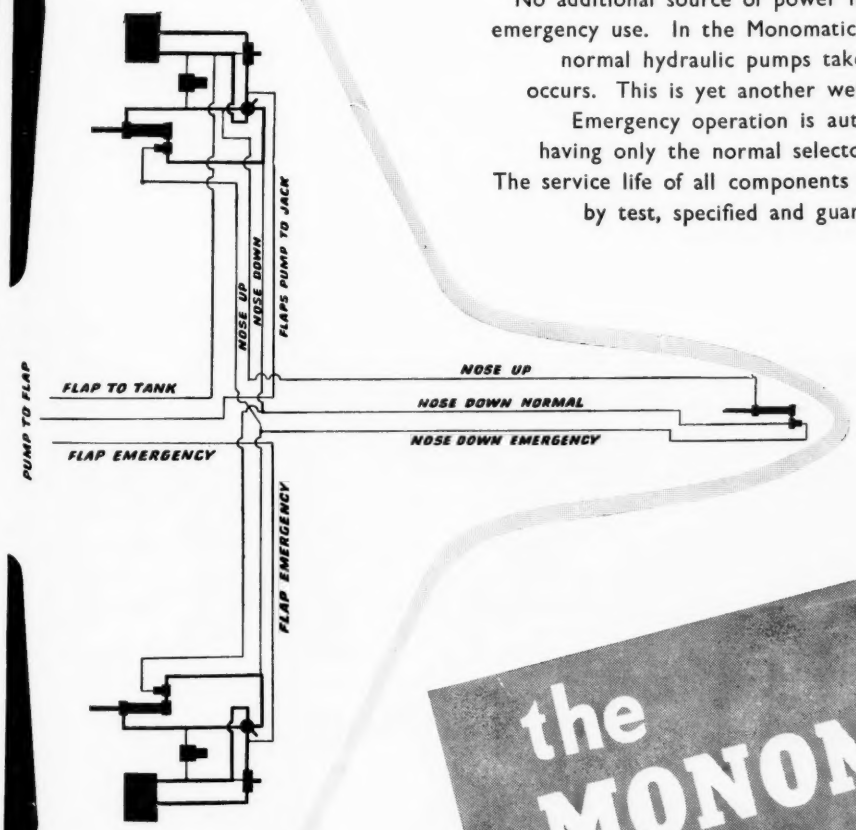

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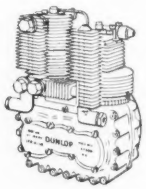
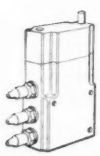
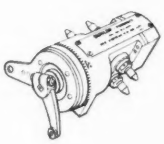
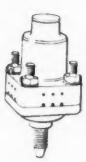
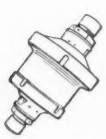
THE MARK I **COMPRESSOR**  *a 3,000 p.s.i. supercharged unit maintaining ground level performance up to 30,000 ft.*

 **SELECTOR VALVES** *of various types for use in conjunction with pneumatic rams to operate all aircraft services.*

The **INFINITELY VARIABLE**  *follow up control for multi-position flap operation,* **PRESSURE RELIEF VALVES**  *with a wide selection of blow-off pressures and supplementary units such as*  **FUEL PRESSURISATION VALVES** *which deliver a high rate of flow at low output pressure.*

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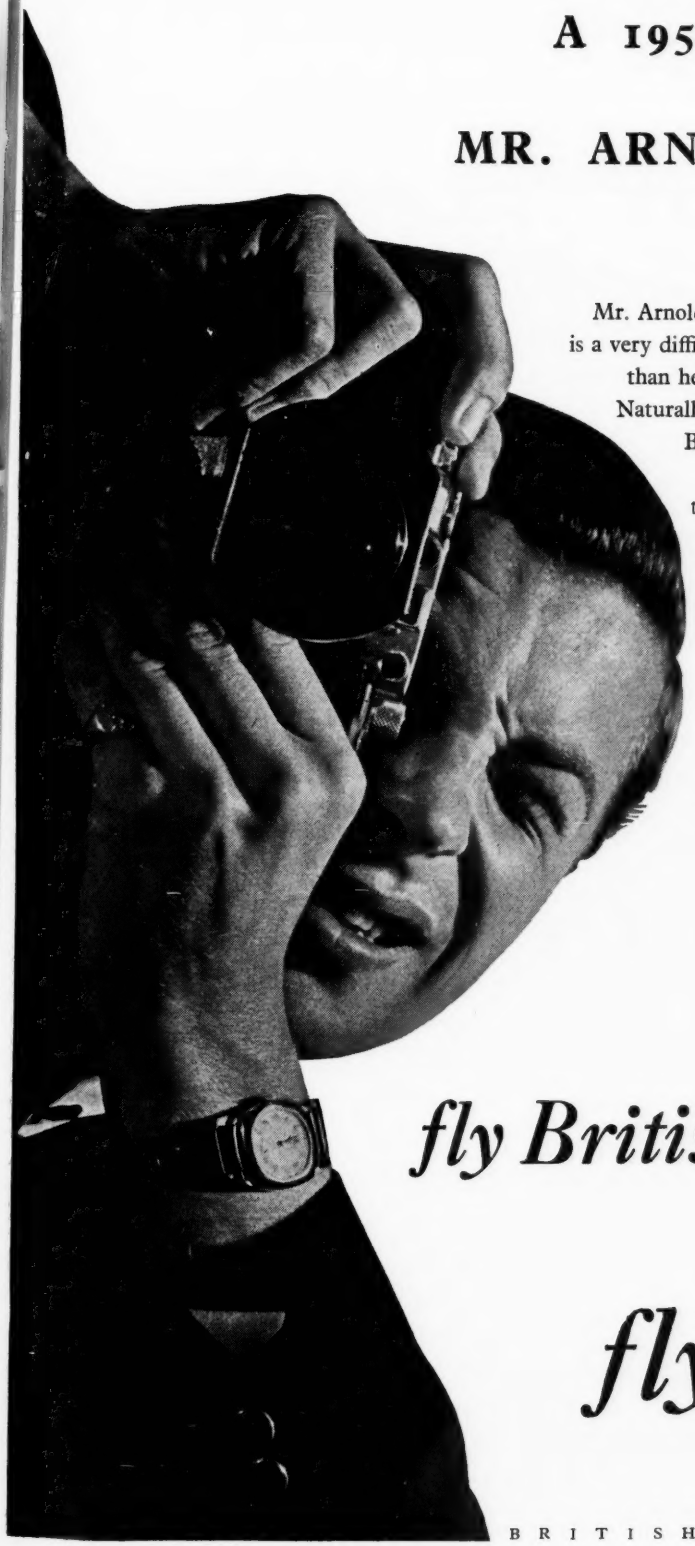

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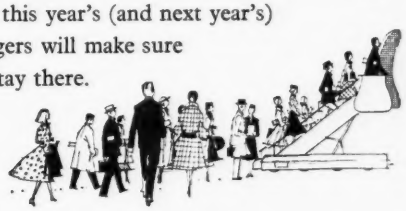

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CONTENTS

PAGE

Notices IX

Nomination of Candidates for Council, 1954—Election of Fellows—Honours Awarded to Members—Institute of the Aeronautical Sciences—New Year's Honours List—News of Members—Acknowledgments—Diary—Other Institution Lectures—LOST PROPERTY—Graduates' and Students' Section ANNUAL GENERAL MEETING—Associate Fellowship Examination Results—Elections—Annual Subscriptions—Journal Binding.

A Quantitative Study of Instrument Approach — J. F.W. MERCER — 83

The Determination of Turbulent Skin Friction by Means of Pitot Tubes — J. H. PRESTON — 109

The Analysis of Shear Distribution for Multi-cell Beams in Flexure by Means of Successive Numerical Approximations — DEREK R. SAMSON — 122

The Fiftieth Anniversary of Powered Controlled Flight—Dinner 128

Technical Notes 138

The Centre of Shear for Sections Bounded by Two Circular Arcs. L. G. WHITEHEAD and L. A. MCQUILLIN—The Use of Glass Cloth/Resin Moulded Components in the Laboratory. F. G. IRVING and R. A. SAUNDERS—Wind Tunnel Balance Design: The Simultaneous Measurement of Forces and Moments. C. G. SAUNDERS—Definition of Specific Impulse. F. W. THORNE.

The Library 144

REVIEWS:—Modern Developments in Fluid Dynamics—High Speed Flow—Statistics for Technologists—Petroleum and Performance—Lubricant Testing—Basic Mechanics of Fluids—The Atomisation of Liquid Fuels—The Dimensioning of Engineering Drawings—Feathered Wings—The Winged Life—A Portrait of Antoine de Saint Exupéry, Poet and Airman—Aviation Facts and Figures.

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NOTICES

An annual sum of £250 is available for premium awards for papers, including Technical Notes, published in the Journal. Members and non-members of the Society are invited to submit papers on any aspect of aeronautics

Nomination of Candidates for Council, 1954

The following is an extract from the By-Laws:—

"The Twenty-one ordinary members (of the Council) shall be nominated and elected from among the members of the Society. At the date of their election at least ten shall be Fellows, and one at least shall be in each of the following classes: Associate Fellow, Associate and Graduate.

"Of the ordinary members of the Council, that number necessary to create seven vacancies shall retire annually. The retiring members shall be those with the longest service since their last election but they shall be eligible for re-election.

"Nominations of candidates for election to the Council must be received by the Secretary not later than *10th April* in each year and shall include statements in writing by the candidates that they are willing to serve. The nomination forms shall be signed by one proposer and two seconders, all of whom shall be voters."

Nomination forms may be obtained on application to the Secretary.

Election of Fellows

The attention of Members is drawn to the following extract from the Society's By-Laws:—

"Fellows shall comprise every person who on the 30th day of January 1950 was on the Register as a Fellow of the Society; and every person thereafter awarded the honour of Fellowship.

"Elections to Fellowship will be made annually by the Council and will be announced at the Annual General Meeting of the Society. Nominations will be initiated by the members of the Council or by any four Fellows of the Society. It is the duty of the Council to see that the honour is awarded only to persons who have attained a considerable degree of technical eminence in the profession of aeronautics."

From the above it will be seen that any four Fellows may nominate a suitable candidate for Fellowship.

Honours Awarded to Members

Sir William S. Farren, President of the Society, has been awarded an *Honorary Fellowship* of the Institute of the Aeronautical Sciences, for his contribution to the advancement of aeronautics. Only one award to a non-American national is made each year.

Mr. N. E. Rowe, Member of Council, has been awarded a *Fellowship* of the Institute of the Aeronautical Sciences. Normally only two awards are made annually to non-American nationals.

Dr. L. Aitchison, *Fellow*, has been awarded the Platinum Medal of the Institute of Metals for his services "in industry, education, and the public service."

Institute of the Aeronautical Sciences Elections for 1954

J. L. Atwood, President of North American Aviation Inc., has been elected President of the Institute of the Aeronautical Sciences for 1954.

Four Vice-Presidents elected for the current year are W. A. M. Burden, of William A. M. Burden and Co.; E. S. Thompson, Manager-Contracts, of General Electric's Aircraft Gas Turbine Division; E. T. Price, President and General Manager of Solar Aircraft; and J. W. Larson, Chief Engineer of the Fort Worth (Texas) Division of Consolidated Vultee.

New Year's Honours List 1954

The following members were included in the New Year's Honours List:—

Order of the British Empire (O.B.E.)
Captain W. Baillie (*Associate Fellow*)
R. K. Cushing (*Associate Fellow*)

Appointment to the Royal Victorian Order (Member, Fifth Class)
Flight Lieutenant E. W. Lamb (*Associate*)

Queen's Commendation for Valuable Service in the Air
Captain T. H. Farnsworth (*Associate Fellow*)

News of Members

E. P. Bernat (*Associate Fellow*) has taken up a new post as Lecturer in Mechanical Engineering at the University of Sheffield.

H. B. Cundall (*Associate Fellow*), formerly with the Air Registration Board, has joined Hunting Air Transport Ltd. as Development Engineer.

E. B. Dove (*Associate*) has joined the board of Vicome & Co. Ltd., Bourne, as Technical Director. He was formerly Designer in Charge (Structures) with the English Electric Co., Luton.

Major J. V. Holman (*Associate Fellow*) has been appointed Aviation Consultant to William Sugg & Co. Ltd., engineers, Westminster.

W. E. P. Johnson (*Associate Fellow*), who recently resigned from Power Jets (Research and Development) Ltd., has joined Solar Aircraft Company of San Diego, California, to develop their European interests.

Captain A. C. Loraine (*Associate Fellow*) had the Honour of Member of the Victorian Order conferred on him by Her Majesty the Queen.

W. F. Murray (*Associate Fellow*) has been appointed Airport Commandant at Liverpool. He was formerly Deputy Director Civil Aviation Branch, British Zone of Germany.

F. H. Pollicutt (*Fellow*) has been appointed Chief Designer to Percival Aircraft Ltd. He was formerly Chief Designer at Folland Aircraft Limited.

J. E. Serby (*Fellow*) has been appointed Director-General of Guided Weapons at the Ministry of Supply. He was previously Deputy Director of the Royal Aircraft Establishment.

S. J. Smyth (*Associate Fellow*) has been appointed Chief Aerodynamicist of the design department of Messrs. Aviation Trades (Engineering) Ltd.

Flight Lieutenant L. C. Woods (*Associate Fellow*), of the New Zealand Scientific Defence Corps, who has been seconded to the Aerodynamics Division of the National Physical Laboratory for the past year or two, has resigned his commission in the R.N.Z.A.F. and left England at the end of January to take up an appointment as Senior Lecturer in Applied Mathematics at the University of Sydney.

A. H. Yates (*Associate Fellow*), formerly a Senior Lecturer in the Department of Aerodynamics at the College of Aeronautics, has been appointed Principal of the City of Bath Technical College and takes up his new post on 1st April.

Acknowledgments

The Council acknowledge with grateful thanks the return of back numbers of the Journal from Group Captain E. G. M. Neville, *Associate Fellow*.

Diary

LONDON

February 11th

MAIN LECTURE. Recent Developments in the Structural Approach to Aeroelastic Problems. Dr. D. Williams. At the Institution of Mechanical Engineers, Storey's Gate, S.W.1. 6 p.m. (Tea at 5.30 p.m.)

February 18th

SECTION LECTURE. Helicopter Research. (Joint Lecture with the Helicopter Association). F. O'Hara. 4 Hamilton Place, W.1. 7 p.m.

February 24th

GRADUATES' AND STUDENTS" SECTION. Aircraft Plastics. Lorne Welch. 4 Hamilton Place, W.1. 7.30 p.m.

March 2nd

SECTION LECTURE. Metal Sandwich Construction. F. Tyson. 4 Hamilton Place, W.1. 7 p.m.

March 4th

MAIN LECTURE AT THE BRISTOL BRANCH. First Barnwell Memorial Lecture. Major G. P. Bulman. Royal Fort Physics Laboratory, Bristol. 7 p.m.

March 10th

PARIS.—THE SEVENTH LOUIS BLERIOT LECTURE. The Domain of the Helicopter. R. Hafner.

GRADUATES' AND STUDENTS' SECTION. Annual General Meeting. 7.30 p.m. Followed by the film, "Powered Flight—The Story of the Century." 4 Hamilton Place, W.1. Coffee, 7-7.30 p.m. *Admission to the film is by ticket only.*

March 16th

SECTION LECTURE. The Development of the Spill Flow Burner and its Control System for Gas Turbine Engines. F. H. Carey. In the Library, 4 Hamilton Place, W.1. 7 p.m.

March 25th

GRADUATES' AND STUDENTS' SECTION. Airworthiness Requirements for Landing and Take-off. L. J. W. Hall. In the Library, 4 Hamilton Place, W.1. 7.30 p.m.

March 30th

SECTION LECTURE. Interaction between Shock Waves and Boundary Layers and its Importance in High-Speed Flight. Dr. D. W. Holder. 4 Hamilton Place, W.1. 7 p.m.

April 6th

SECTION LECTURE. A Review from the Design Aspect of Materials used in Rocket Motors. G. O. Jones. 4 Hamilton Place, W.1. 7 p.m.

April 8th

MAIN LECTURE AT THE CHESTER BRANCH. Practical Experience of Airline Engineering. R. C. Morgan. Grosvenor Hotel, Chester. 7.30 p.m.

April 13th

SECTION LECTURE. Some Aspects of Modern Aircraft Materials. Dr. H. Sutton. 4 Hamilton Place, W.1. 7 p.m.

April 22nd

MAIN LECTURE. Diesel Compound Engines. E. E. Chatterton. At the Institution of Mechanical Engineers, Storey's Gate, S.W.1. 6 p.m. (Tea 5.30 p.m.)

April 27th

SECTION LECTURE. Aerodynamic and Aeroelastic Characteristics of the Crescent Wing. G. H. Lee. In the Library, 4 Hamilton Place, W.1. 7 p.m.

April 29th

GRADUATES' AND STUDENTS' SECTION. Fuselage Structural Design Methods. R. J. Jupe. 4 Hamilton Place, W.1. 7.30.

BRANCHES

February 9th

Belfast.—Engineering Problems of Airline Operations. B. S. Shenstone. Kerr Room, Kensington Hotel, Belfast. 7 p.m.

Boscombe Down.—Film Show. "Powered Flight—The Story of the Century" and "Crash Fire Studies." Main Dining Hall, Airmen's Mess, Boscombe Down. 5.30 p.m.

February 10th

Bristol.—Joint Meeting with the Institute of Production Engineers.

Weybridge.—Navigational Aids. Wing Commander G. N. Macintosh, O.B.E. Vickers-Armstrongs Ltd. 6 p.m.

February 12th

Glasgow.—Film Evening. (The R.Ae.S.—Shell Film "Powered Flight—The Story of the Century" will be among those shown.) Royal Technical College. 7.30 p.m.

February 15th

Halton.—Junior Members' Night. Branch Hut, R.A.F. Station, Halton. 6.45 p.m.

February 16th

Belfast.—The Short Analogue Computor. E. Lloyd-Thomas. Canteen, Short Brothers and Harland Ltd. Castlereagh, Belfast. 7 p.m.

February 17th

Coventry.—The Development of the Bristol Proteus Turbine Engine. Dr. S. G. Hooker. Wine Lodge, Coventry. 7.30 p.m.

Hatfield.—Modern Motor Vehicle Production Methods with Special Reference to Jaguar Cars. J. Silver. de Havilland Restaurant, Hatfield. 6.15 p.m.

Manchester.—The Rocket Power Plant. S. Allen. Reynolds Hall, College of Technology, Manchester. 7.30 p.m.

Southampton.—Branch Prize Papers. Institute of Education, University of Southampton. 7 p.m.

February 18th

Leicester.—Present Trends in Aircraft Materials and Construction. W. A. Baker. Leicester College of Technology. 7.15 p.m.

February 22nd

Henlow.—Annual General Meeting and Film "Powered Flight—The Story of the Century." R.A.F. Technical College, Henlow. 7.30 p.m.

February 23rd

Belfast.—Some Aspects of the Flutter Problem. N. P. Shevloff. Reception Room, Kensington Hotel, Belfast. 7.30 p.m.

February 24th

Weybridge.—The Shape of Wings to Come. D. Keith-Lucas. Vickers-Armstrongs Ltd., Weybridge. 6 p.m.

February 25th

Isle of Wight.—Accident Investigation. Air Commodore Sir Vernon Brown. Clubhouse, Saunders-Roe Sports and Social Club, Church Path, E. Cowes. 6.30 p.m.

February 26th

Birmingham.—The Development of the Vickers Viscount. A. Greenwood. Birmingham Chamber of Commerce. 7.30.

March 1st

Halton.—Films. Branch Hut, R.A.F. Station, Halton. 6.45 p.m.

March 2nd

Boscombe Down.—Air Transport—Present Problems and Future Prospects. P. G. Masefield. Main Dining Hall of the Airmen's Mess, Boscombe Down. 5.30 p.m.

March 3rd

Brough.—Ship Design and Construction. A. Hunter. Lecture Hall, Electricity Buildings, Ferensway, Hull. 7.30 p.m.

Chester.—Peacetime Use of Atomic Energy. L. A. Rotherham. Grosvenor Hotel, Chester. 7.30 p.m.

March 4th

Bristol.—MAIN SOCIETY LECTURE. First Barnwell Memorial Lecture. Major G. P. Bulman. Royal Fort Physics Laboratory, Bristol. 7 p.m.

March 8th

Glasgow.—Aircraft Design. R. L. Lickley. Royal Technical College, Glasgow. 7.30 p.m.

Halton.—Fatigue: What it is and Some Ways of Reducing its Incidence. Major P. L. Teed. Branch Hut, R.A.F. Station, Halton. 6.45 p.m.

Henlow.—Bird Flight. Captain J. Laurence Pritchard. R.A.F. Technical College, Henlow. 7.30 p.m.

March 9th

Belfast.—Guided Weapons. W. Stephens. Kerr Room, Kensington Hotel, Belfast. 7 p.m.

March 10th

Southampton.—The Design of Target Aircraft. R. J. B. Woodhams. Institute of Education, University of Southampton. 7 p.m.

March 15th

Derby.—Social Function. Rolls-Royce Welfare Hall, Nightingale Road, Derby. 6.15 p.m.

Halton.—Branch Night. Branch Hut, R.A.F. Station, Halton. 6.45 p.m.

March 17th

Hatfield.—Integral Construction. E. D. Keen. de Havilland Restaurant, Hatfield. 6.15 p.m.

Manchester.—Sandwich Construction Applied to Aircraft Structure. W. G. Heath. Reynolds Hall, College of Technology, Manchester. 7.30 p.m.

Preston.—Aircraft Production Control. F. H. E. Maidment. Technical College, Preston. 7.30 p.m.

Weybridge.—Operating Viscounts. Captain A. S. Johnson. Vickers-Armstrongs Ltd., Weybridge Works. 6 p.m.

March 18th

Isle of Wight.—Branch Prize Lectures. Clubhouse, Saunders-Roe Sports and Social Club, Church Path, East Cowes. 6.30 p.m.

March 22nd

Halton.—Junior Members' Night. Branch Hut, R.A.F. Station, Halton. 6.45 p.m.

Henlow.—Student Members' Lectures. R.A.F. Technical College, Henlow. 7.30 p.m.

March 23rd

Belfast.—Some Aspects of Resistance Strain-Gauging. G. A. Lewis. Reception Room, Kensington Hotel, Belfast. 7 p.m.

March 26th

Birmingham.—Lecture on Delta Aircraft. Birmingham Chamber of Commerce, New Street. 7.30 p.m.

Southampton.—Annual Dance.

March 31st

Bristol.—Aeronautical and Mechanical Engineering 1929-1954—A Retrospect and a Prospect. Wing Cdr. T. R. Cave-Brown-Cave. Joint meeting with the Institution of Mechanical Engineers. Royal Fort Physics Laboratory, Bristol. 7 p.m.

Brough.—Annual General Meeting and Films. Lecture Hall, Electricity Buildings, Ferensway, Hull. 7.30 p.m.

April 2nd

Leicester.—Supersonic Bangs. G. M. Lilley. Loughborough College, Loughborough. 7.15 p.m.

April 5th

Derby.—Some Aspects of Airline Flying with Jet Aircraft. Captain W. G. Johnson. Welfare Hall, Rolls-Royce. 6.15.

April 6th

Belfast.—Annual General Meeting and Film Show. Kerr Room, Kensington Hotel, Belfast. 7 p.m.

Glasgow.—The Piston Engine and the Development Engineer. J. M. Marshall. Royal Technical College. 7.30.

April 7th

Bristol.—Annual General Meeting and Film Show. Conference Room, Filton House, Bristol Aeroplane Co. 6 p.m.

Weybridge.—Brains Trust. Vickers-Armstrongs Ltd., Weybridge Works. 6 p.m.

April 8th

Chester.—MAIN SOCIETY LECTURE. Practical Experience of Airline Engineering. R. C. Morgan. Grosvenor Hotel, Chester. 7.30 p.m.

THE BELFAST BRANCH

The Editor regrets sincerely that the lectures for the Belfast Branch given in the January Diary were sadly mixed and apologises for any inconvenience caused to the Branch and to members. The meetings for the Belfast Branch given in the February Diary are correct as at the 21st January.

LECTURES OF INTEREST TO MEMBERS

Imperial College of Science and Technology

Professor A. Kantrowitz, of Cornell University, will be giving a series of four lectures on "Physics of Shock Waves" in the Royal School of Mines, Imperial College, Room 153, entrance in Prince Consort Road, at 5 p.m. on the following dates: 8th, 9th, 22nd and 23rd February 1954. (Tickets not required.)

Royal Institution

Mr. Hayne Constant, C.B.E., F.R.S. (*Fellow*), is lecturing to the Royal Institution, 21 Albemarle Street, on 12th March 1954 on "The Search for Lightness." Particulars may be obtained from the Secretary, The Royal Institution.

Royal United Service Institution

Marshal of the Royal Air Force Sir John Slessor, G.C.B., D.S.O., M.C., will lecture to the Royal United Service Institution, Whitehall, S.W.1, on "Air Power and the Future of War" on 31st March 1954.

University College—Lectures on Air Law

A special course of Lectures on Air Law, to be given one night a week, has been started by the Faculty of Laws, University College, London, for the Spring and Summer Terms 1954. The fee for the course is £4 4s. 0d., which includes a registration fee of 10s. 6d. Full particulars may be obtained from the Faculty Office, Faculty of Laws, University College, London.

LOST PROPERTY

The Secretary has been informed that a lady's fur was found at the Dorchester Hotel following the Dinner on the 17th December. If members have any information regarding the loss would they please write to the Secretary.

GRADUATES' AND STUDENTS' SECTION—ANNUAL GENERAL MEETING

The Annual General Meeting of the Section will be held at the Society, 4 Hamilton Place, W.1, on Wednesday, 10th March 1954, at 7.30 p.m. Light refreshments will be available from 7 to 7.30 p.m. The meeting will be followed by a showing of the film "Powered Flight—The Story of the Century." *Admission to the film will be by ticket only and since accommodation is limited, early application is advisable.*

AGENDA

1. To consider and approve the Minutes of the previous Annual General Meeting.
2. To consider any business arising from these Minutes.
3. To receive the report of the Committee on the activities of the Committee and of the Section during the past year.
4. To make recommendations to Council on the names of the representatives of the Section to serve on the Committee for the year 1954-55.
5. To receive the rules for the administration of the Section.
6. To discuss the future activities of the Section.
7. To consider any other business connected with the affairs of the Section.

Nominations for the Section representatives on the Committee should be sent to the Hon. Secretary before the 8th March or may be handed in at the meeting. They must be signed by the candidate, proposer and seconder who must all be Graduates or Students. The number of vacancies to be filled is nine and if the nominations exceed this number, a ballot will be held at the meeting. The successful candidates' names will be subject to confirmation by Council. Members are reminded that it is desirable for the Committee to be representative of as many firms and colleges as possible.

Following Council's recent resolution to appoint the Chairman of its Committees, the rules of the Section relating to this appointment are to be amended. Copies of the proposed new rules to be presented at the Annual General Meeting may be obtained from the Society.

ALAN E. BROCK, *Honorary Secretary.*
77 Broughton Road, Thornton Heath, Surrey.

Associate Fellowship Examination Results

The following were successful in the Associate Fellowship Examinations held in December 1953:—

Part I—Home

V. Angre, Applied Mathematics, Properties of Matter, Theory of Machines.

J. W. Gardner, Aerodynamics I. D. Gill, Properties of Matter, Aerodynamics I, Strength of Materials I.

S. M. Humphry, Pure Mathematics, Properties of Matter, Aerodynamics I, Strength of Materials I.

D. O. Lewis, Aerodynamics I, Theory of Machines.

A. E. Moniz, Strength of Materials I, Theory of Machines.

R. A. Nicol, Applied Mathematics, Properties of Matter, Strength of Materials I, Theory of Machines.

T. O'Brien, Pure Mathematics, Aerodynamics I, Theory of Prime Movers.

J. L. Rudkin, Applied Mathematics, Properties of Matter, Strength of Materials I, Theory of Machines.

Part I—Abroad

J. Klaver (Amsterdam), Pure Mathematics, Magnetism, Electricity, Aerodynamics I, Theory of Prime Movers.

B. R. Srinivasa Murthy (Bangalore, India), Aerodynamics I, Strength of Materials I.

S. L. Relan (Agra (U.P.), India), Pure Mathematics, Magnetism, Electricity, Strength of Materials I, Theory of Prime Movers.

J. M. De Wilde (Amsterdam), Pure Mathematics, Magnetism, Electricity, Aerodynamics I, Theory of Prime Movers.

Part II—Home

W. B. Blydenstein, Engine Design.

S. R. Cann, Aircraft Design.

A. H. Fraser-Mitchell, Aerodynamics II.

D. R. Henbest, Air Transport, Aircraft Materials.

T. C. Lee, Strength of Materials II. R. Lewis, Aircraft Design.

W. H. McKinlay, Radio Communications. J. McNaughton, Aircraft Design.

J. G. H. Pearce, Engineering Economics.

N. R. Reddy, Strength of Materials II. D. J. Richardson, Aerodynamics II. D. M. Ridland, Aerodynamics II.

S. S. Singh, Strength of Materials II. Tara Singh, Engine Design.

D. H. Tipper, Aerodynamics II. I. K. Trundley, Aircraft Design.

F. I. V. Walker, Aircraft Design.

Part II—Belfast

E. S. Bradley, Strength of Materials II. J. Burnett, Strength of Materials II.

Part II—Abroad

W. K. Aiyadurai (Melbourne), Aircraft Design.

Y. V. Badri Nath (Bangalore, India), Strength of Materials II.

Annual Subscriptions

Members are reminded that their annual subscriptions became due on 1st January 1954. The rates are:—

	Home			Abroad		
	£	s.	d.	£	s.	d.
Fellows	5	5	0	4	4	0
Associate Fellows	4	4	0	3	3	0
*Associates	3	3	0	3	3	0
Graduates (aged under 26)	2	2	0	2	2	0
Graduates (aged 26 and over)	2	12	6	2	12	6
Students (aged under 21)	1	1	0	1	1	0
Students (aged 21 and over)	1	11	6	1	11	6
Companions	3	3	0	3	3	0
Founder Members	2	2	0	2	2	0

* Any Associate elected before 1st October 1947 may, if he wishes, elect not to receive the Journal, and in this case his subscription will be reduced by £1 1s. 0d. to £2 2s. 0d.

It will avoid delay and confusion if members, when sending remittances for subscriptions, will state their names clearly and give their addresses and grades of membership. Remittances should be made payable to the Royal Aeronautical Society.

Elections

The following is a list of new members and transfers of membership:—

Associate Fellows

Rene M. Bloch (*from Graduate*)
Geoffrey Percival Dollimore (*from Graduate*)
John Cecil Gibbings (*from Graduate*)
Charles Erling Gjertsen Payne (*from Student*)
Henry John Russell
Wilfred Taylor (*from Graduate*)
Robert Hugh Williams (*from Graduate*)

Associates

Rupert Allan Clark
Timothy William Delury
John Parkinson (*from Graduate*)
Bennett Price
Edward Henry Charles Tullett

Graduates

Reginald Gene Austin
Serge Dassault
Leslaw Jerzy Jelonek (*from Student*)
Michael George Marsh
Robert Barry Matthews
Colin Leslie Munro
Peter Frederick Orchard (*from Student*)
Herman Sholom Pearlman
Elvie Lawrence Smith

Students

Willem Benjamin Heyerdahl Blydenstein
James Arthur Browne
Peter Richard Daughtry
Alexander William Gray
John Harrod
Bryan Davies Hope
John Charles Patrick Northall
Robert Sewell
Michael John Sparks

Changes of Address

To assist in keeping the records of members correct and up to date the Secretary will be glad if all members will notify him as soon as possible of changes of address.

When notifying changes please give the following particulars:—

Name (in block letters). New address (in block letters).
Grade of membership. Old address.

Changes of address must be received *before the 15th of the month in order to be effective for the* Journal for the following month.

Journal Binding

Self-Binder Cases

Self-Binder cases of the "Easibind" type are available from the offices of the Society. These binders are for members who do not have their Journals permanently bound, or who wish to keep their Journals together during the year for binding later.

These cases will hold 12 Journals which are kept in place by means of flexible steel wires. Journals can be inserted or withdrawn easily without damage, so preserving the contents for permanent binding later. The Journals will open flat at any page.

The binder is strongly made in durable dark blue leather cloth on stiff board covers and has gold lettering on the spine. The year is not blocked on the spine but there is a panel on which members who wish to use the binder as a permanent case can put the date.

The cost is 11s. 6d. each including postage and packing for either the size to fit 1952 and previous Journals, or for the size to fit the Journal from January 1953, which has been increased in size. Orders and remittances should be sent direct to the Secretary at the Offices of the Society and it is *important to state whether the old size or new size is required.*

Permanent Binding

There is no increase in the price of permanent binding of Journals. The prices are:—

1953 Volume (including packing and postage) 16s. 0d.
Previous Volumes (including packing and postage) 18s. 0d.

Journals, *with a note of the name and address of the sender,* should be sent direct to The Lewes Press, Friars Walk, Lewes, Sussex, and the remittance to the Secretary at the Offices of the Society.

The Journal of the Royal Aeronautical Society

WITH WHICH IS INCORPORATED THE INSTITUTION OF AERONAUTICAL ENGINEERS

VOLUME 58 FEBRUARY 1954 NUMBER 518

A Quantitative Study of Instrument Approach

by

J. F. W. MERCER, B.Sc., A.C.G.I.

(Blind Landing Experimental Unit, Ministry of Supply)

The 887th Lecture to be given before the Royal Aeronautical Society was held at the Institution of Mechanical Engineers, Storey's Gate, London, S.W.1, on 29th October 1953, and was presided over by Sir William Farren, C.B., M.B.E., M.A., F.R.S., F.R.Ae.S., President of the Society. Sir William said that this was the first main lecture of the session. In one paragraph of his paper Mr. Mercer said that those who were specialists in fields of a highly specialised kind should get together with their friends in other branches of aeronautics, otherwise they might all go on in ignorance of what was being done by others; he hoped therefore, that there were a number of specialists present who would join in the discussion.

Introducing the Lecturer, Sir William said that he had known Mr. Mercer for many years; Mr. Mercer had joined the Blind Landing Experimental Unit at Martlesham Heath when it was formed and it was there that he had done the work described in the paper. The President said he had always felt that one of the things most needed for the real development of aviation was a means of landing in bad weather. He hoped that Mr. Mercer's paper was a contribution towards that end; it was concerned with one phase only of blind landing—approach—but he hoped there would be other papers on the subject. He now called on Mr. Mercer to give his paper.

1. Introduction

The problem of approach and landing under poor visibility conditions has been with aviation since its earliest days and has been the subject of attention in many countries during the past 25 years. Complete independence of weather conditions has yet to be achieved on an operational basis and the current technique is to use an instrument approach system to bring the aircraft down to a height of the order of 200 ft. and to rely on visual guidance provided by high-intensity lights or runway markings for the completion of the landing from that height. Standardisation of the aids to be used has been achieved within civil aviation, and I.C.A.O. has issued comprehensive specifications for a radio approach aid I.L.S. (Instrument Landing System)[1] and for standard configurations of visual aids[2]; equipment to these specifications has been installed on many airfields. The value of this equipment can ultimately be measured only in terms of the degree of independence of weather conditions which is achieved and it is commonly recognised that for the maximum benefit to be attained a full understanding of the many problems involved is essential. In a notable paper before the Society Calvert[3] outlined the problems peculiar to the visual guidance phase of the overall manoeuvre, basing his work on a quantitative study of the principles involved. The present paper describes work on the instrument approach phase of the manoeuvre and every attempt has been made to maintain a quantitative attack wherever possible.

The basis of the paper is work conducted at the Blind Landing Experimental Unit of the Ministry of Supply during the past few years on the problem of coupling I.L.S. information into an automatic pilot to give accurate blind approaches, but the discussion has not been confined to this limited field. Some of the results have a direct bearing on the problems facing a pilot called upon to make an I.L.S. approach manually, and the technique developed to assess on a scientific basis the relative merits of two methods of control is thought to have application to the whole field of blind approach and could usefully be used to determine the relative merits of competing systems, or to assess the claims commonly made for new methods of presenting I.L.S. information.

Notation

σ	angle from centre line of I.L.S. localiser
ϕ	bank angle
ψ	heading
ψ_D	heading datum
W	cross wind component
V	velocity
θ	pitch attitude
θ_D	pitch datum
β	angle from centre line of I.L.S. glide path
y	displacement from centre line of I.L.S. localiser
t	time
k_1, k_2, etc.	constants

2. Automatic Approach

2.1. BASIC EQUIPMENT

The experiments at the Blind Landing Experimental Unit have used almost exclusively radio systems of the

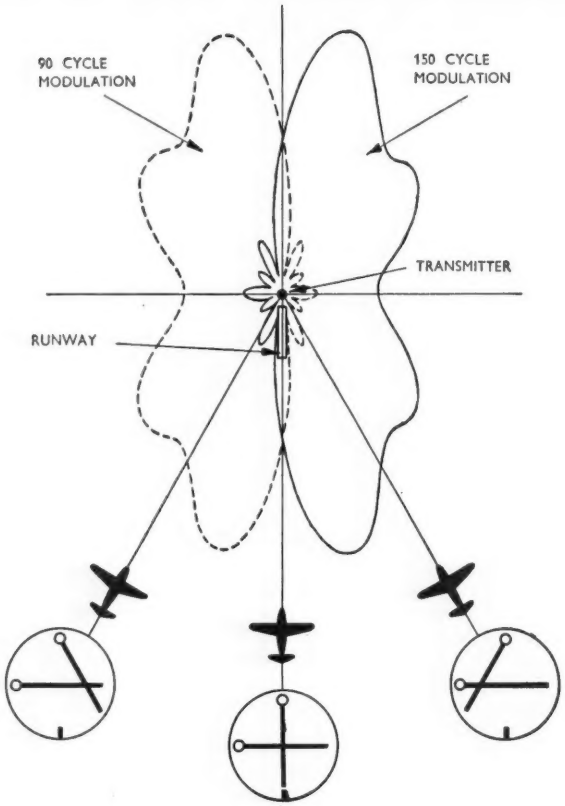

FIGURE 1(*a*). Localiser—horizontal radiation patterns.

I.L.S. type and automatic pilots manufactured by S. Smith & Sons. The I.L.S. system is based on the earlier S.C.S.51 equipment. A localiser transmitter emits coded signals in overlapping beams as indicated in Fig. 1(*a*), the resultant output of the airborne receiver being a direct current which is a measure of the angle between the line joining the transmitter to the aircraft and the equisignal line of the localiser which, in general, is made to coincide with the centre line of the runway. A glide path transmitter similarly produces coded signals in overlapping beams in the vertical plane, as shown in Fig. 1(*b*), the output of the associated airborne receiver being a direct current which is a measure of the angle between the line joining the aircraft to the transmitter and the equisignal line of the glide path which is commonly set at an angle of 3° emanating from a point near touchdown. These two signals are applied to a cross-pointer meter, as shown in Fig. 2. Further details of the equipment have been given by Pritchard[4].

The automatic pilot used in the experiments has been the subject of development during the work but has remained essentially to the design described by Meredith in 1949[5], although magnetic amplifiers have now replaced the original electronic amplifiers and there have been other detailed design changes. For the purposes of blind approach it may be viewed as an equipment which will control the aircraft in pitch and roll in accordance with low level D.C. input signals.

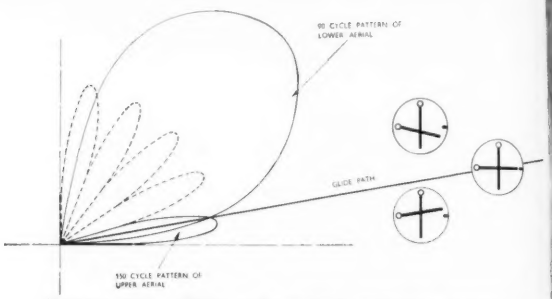

FIGURE 1(*b*). Glide path vertical radiation patterns.

2.2. THE CONTROL PROBLEM—HORIZONTAL PLANE

For an aircraft in a position such as that shown in Fig. 3, the I.L.S. equipment will provide a knowledge of the angle σ and the automatic pilot is available to bank the aircraft in accordance with demanded inputs. If the I.L.S. signal alone were fed into the automatic pilot to demand a bank angle or rate of turn proportional to it, it is apparent that a stable approach would not be achieved because the aircraft would be turned through a continuously increasing angle in approaching the centre line and would over-shoot. To prevent this unstable manoeuvre a term related to the rate of closing the beam must also be introduced. Such a "rate" term is available either by differentiating the beam signal with respect to time (rate stabilisation) or, by using the difference between the known runway direction and the aircraft heading as given by a gyro compass (heading stabilisation). The assessment of the relative operational value of these two methods forms the main burden of the work.

2.2.1. *Rate stabilisation*

The form of control using rate stabilisation may be expressed ideally as

$$\text{Bank angle applied } \phi = k_1 (\sigma + k_2 \dot{\sigma}).$$

It will be noted that all the control information is derived from the beam itself and that the only stable

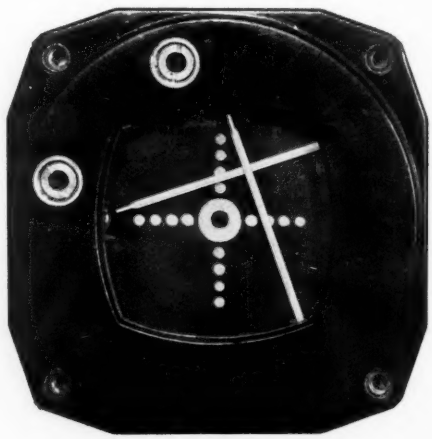

FIGURE 2. Cross-pointer meter.

state is with $\sigma=0$, *i.e.* the aircraft is on the centre line of the beam, and $\dot{\sigma}=0$, *i.e.* the aircraft is tracking along that line. A steady crosswind will not prevent the arrival at this desirable steady state as the aircraft will take up the drift angle necessary to track along the centre line, but the effect of changes in the crosswind component will depend upon the transient performance of the system. The weakness in the system lies in its susceptibility to beam distortion, because unless the beam is perfect in the sense that the relationship between localiser receiver output and angular displacement is linear, the differential of the beam $\dot{\sigma}$ will no longer be a true measure of the rate of approach to the centre line. It may be noted that practical tests indicate that a suitable value of k_2 is of the order of 15 to 20, so that on a short term basis the aircraft is being controlled almost exclusively by the rate term and thus the performance of the control will be determined largely by the degree to which that term is a true measure of the rate of approach to the centre line.

2.2.2. *Heading stabilisation*

The form of control using heading stabilisation may be expressed ideally as

Bank angle applied $\phi=k_3(\sigma-k_4\psi)$ (*see* Fig. 3)

In the absence of crosswind it is apparent that the steady state condition will be once again $\sigma=0$, *i.e.* the aircraft is on the zero-signal line of the beam and $\psi=0$, *i.e.* it is tracking along it. In the presence of a crosswind W the heading necessary to track along the beam is no longer the Q.D.M. of the runway and it may easily be shown that the stable path is no longer along the centre line but along a line displaced on the downwind side of it by an angle given by

$$\frac{k_4}{1+k_4}\,\frac{W}{V}\,.$$

Experiment has shown that a reasonable value for k_4 is 1/10 and as W/V is approximately the drift angle, the steady state line is at an angle to the centre line of about one tenth of the drift angle.

Provided that its value be known, the control may be modified to allow for a crosswind component by changing the control equation to

$$\phi=k_3[\sigma-k_4(\psi-\psi_D)]$$

where ψ_D is the heading required to track along the centre line in the presence of the steady crosswind.

Unfortunately, as the aircraft is descending while being controlled on the localiser beam, the crosswind is rarely steady and in general changes with height. Moreover, the crosswind except at the surface is not known so it is not possible to predetermine the datum ψ_D suitable for any point on the approach other than near touchdown. During early tests attempts were made to overcome this difficulty by moving the datum by means of an integrator. Initially some approximate ψ_D such as the Q.D.M. (magnetic heading) of the runway was set into the equipment and in the presence of a crosswind the aircraft accordingly settled down on a path for which the beam signal was not zero and for which the heading ψ was not equal to ψ_D. To correct this discrepancy an integrator was arranged to rotate the heading datum at a speed proportional to $\psi-\psi_D$. The rate of doing this was critical because if rapid changes of crosswind were to be followed the datum had to be moved quickly, but this movement was in the direction such as to destabilise the approach. The best compromise between these conflicting demands was found to be inadequate to overcome the changes of crosswind encountered on a long series of tests, the standard deviation of the lateral displacement from the runway centre line being over 70 ft. and large errors in position not being compensated to any notable degree by inward tracking velocities. On this evidence the project was abandoned.

The more recent technique consists of obtaining a value of the surface wind speed and direction in the touchdown area and calculating the heading required to track in this area along the centre line of the runway (*i.e.* the Q.D.M.D.), this heading being used as the datum *for the whole approach*. The effect of the technique is that far out on the approach the centre line is not held, the aircraft being offset by an amount proportional to the prevailing crosswind, but as the approach continues and the crosswind changes towards the value obtained on the ground this offset is correspondingly reduced until at touchdown it is zero. It will be shown later that this technique works well in practice and pilots at the Blind Landing Experimental Unit have been quite happy to use it, even under the most adverse weather conditions.

It is convenient at this stage to introduce a small theoretical study to illustrate this point. Fig. 4 gives the theoretical path of an aircraft controlled to follow a localiser beam but subject to a step change of crosswind at a point low down on the approach. The two curves show respectively the paths for heading and rate stabilisation and important differences will be seen between them. The rate stabilised path maintains $\sigma=0$ far out but is thrown away from the centre line by the step change of wind. The heading stabilised path alternatively is offset from the beam far out but is thrown towards the centre line by the step change.

2.3. THE CONTROL PROBLEM—VERTICAL PLANE

The basic problem in the vertical plane is essentially similar to that in the horizontal plane. The I.L.S. glide path system provides positional information relative to

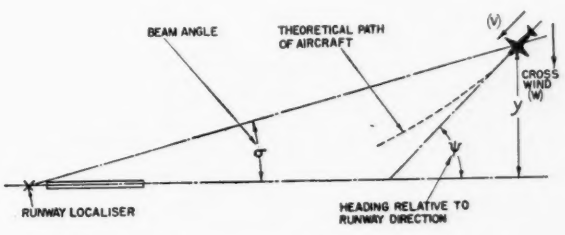

FIGURE 3. Automatic horizontal guidance —explanatory diagram.

a fixed line which it is desired to follow and the automatic pilot is available to control the rate of pitch of the aircraft. The direct coupling of the I.L.S. output to the automatic pilot would lead to instability and a stabilising term is once again required. In principle two solutions, akin to those already described are available, *i.e.* a rate term derived by differentiating the beam signal, or a "heading" term derived from departures of the pitch attitude from a preset datum.

The first of these solutions has been the subject of only a cursory test and the main bulk of the work at the Blind Landing Experimental Unit has used pitch attitude stabilisation. The basic control equation may be expressed as

$$\frac{d\theta}{dt} = -k_6 [\beta + k_5 (\theta - \theta_D)]$$

where β = angular position relative to the glide path

θ = pitch attitude of the aircraft

θ_D = a pitch datum

k_5 and k_6 are constants.

The main problem is the setting of the appropriate pitch datum. On an approach the aircraft is flown at constant height at the approach speed until the glide path is intersected. When the glide path control is engaged the pitch datum θ_D is initially set automatically within the automatic pilot to a value 3° below that found necessary to maintain constant height, 3° being equal to the most usual glide path angle. Simultaneously the pilot is called upon to adjust the throttles to maintain the chosen speed on the glide path. This is normally achieved by one pre-determined reduction of power followed by one or two small corrections. In the presence of fore and aft components of wind, or at a site where the glide path angle is different from 3°, the datum θ_D so set will not be correct and the aircraft will ride high or low on the glide path. Even though in this condition it is aimed at the same point on the runway, it has been found desirable to reset this pitch datum in accordance with the equation

$$\text{Instantaneous Pitch Datum} = \theta_D + k_7 \int (\theta - \theta_D)\, dt.$$

The time constant of the integrator is of the order of 30 seconds and with this value stable accurate control is achieved.

2.4. APPLICATION OF THESE CONTROL SYSTEMS

In practice an automatic approach is divided into two phases. During the first phase—termed "Inbound" or "Track"—the initial turn is made on to the centre line of the localiser beam while the aircraft is maintained at constant height. This phase ends with the intersection of the glide path beam and from this point the aircraft is controlled to follow not only the localiser signals in the horizontal plane, but also the glide path signals in the vertical plane. This latter phase is known as the "Final" phase, although the term "Glide" has also been used. An aircraft flying at 1,500 ft. will intersect a 3° glide path at approximately 5 miles from the runway threshold and it is desirable that the aircraft be settled reasonably near the centre line of the localiser beam at that range. The "Inbound" phase must therefore be initiated at a sufficient distance for the errors at the engaging point to be reduced to a small value and it is desirable that the greatest possible freedom of choice of engaging point be available. Heading stabilisation gives greater freedom than rate stabilisation and is accordingly chosen. With a rate system the manoeuvres of the aircraft would necessarily be limited to the "linear" region of the localiser coverage (approximately ±4°), as otherwise no reliable rate term would be

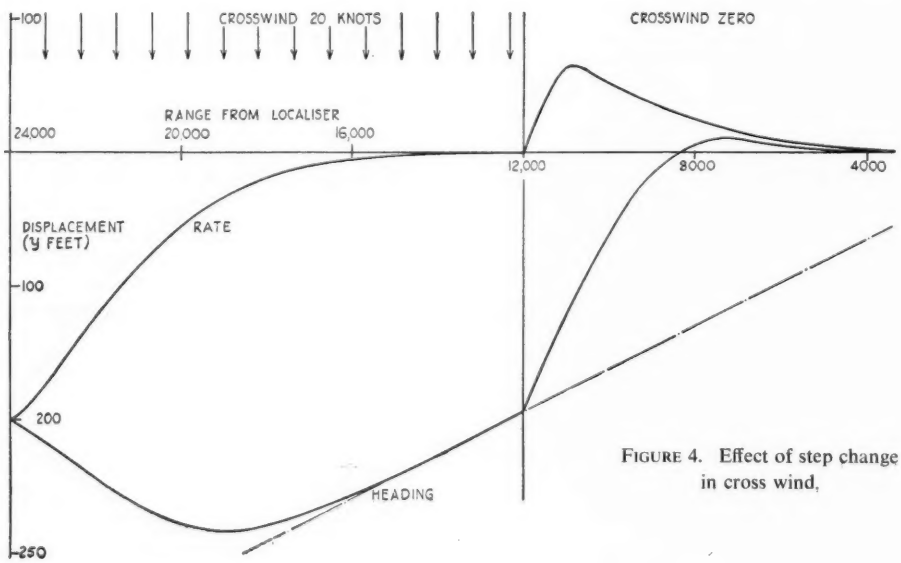

FIGURE 4. Effect of step change in cross wind.

obtained. Heading stabilisation carries no such restriction and in fact, provided that enough range is available, it may be shown that a heading stabilised Inbound control may be engaged anywhere within the coverage of the localiser beam.

Experience leads to the recommendation that the Inbound control be engaged either near the centre line tracking within $\pm 20°$ of the Q.D.M. or alternatively, when tracking at right angles to the beam as soon as the localiser needle comes off its stop, *i.e.* at about $2\frac{1}{2}°$ before the beam centre line. To give still greater freedom and avoid penalty if the control be engaged earlier in the latter conditions, the heading signal is reduced at large angles of heading error. By this means the aircraft, if a long way from the beam, is turned rapidly on to a heading inclined at about 75° to the Q.D.M. until the linear portion of the localiser coverage is reached, when the path will revert to the normal exponential approach and the aircraft will reach its stable path with not more than one small overshoot.

As indicated, the control in the vertical plane is of the form described in Section 2.3.

The great problem is the choice of the best method of holding the localiser centre line during the final phase and this problem occupied the attention of the Experimental Unit for a considerable period. It was apparent that the rate system would be adversely affected to the larger degree by distortion of the localiser beam and the heading system by the effects of crosswinds. It was not known to what extent localiser beams were distorted, or if the crosswind difficulties could be overcome in practice. These problems will be considered in turn.

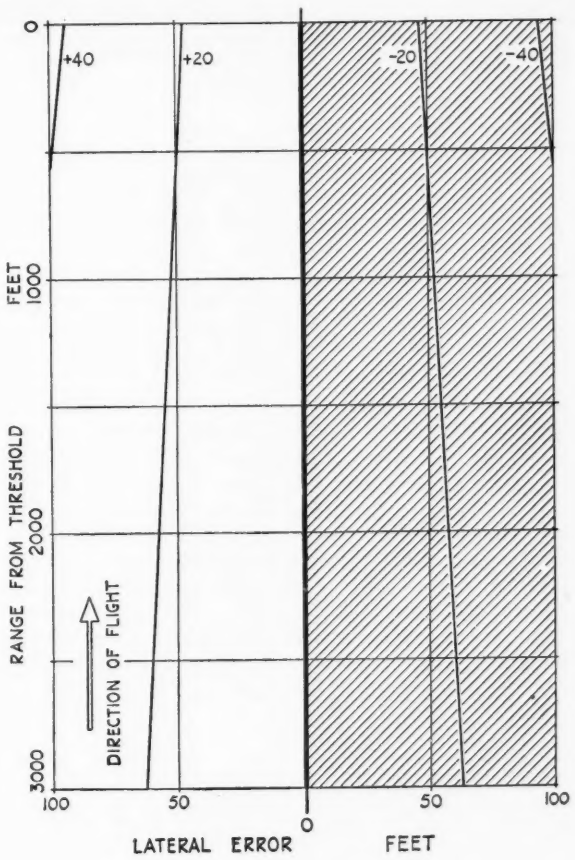

FIGURE 5. Beam contours—no distortion.

3. I.L.S. Beam Distortion

3.1. INTRODUCTION

It is well known that I.L.S. beams suffer from distortion and that this distortion is caused by energy reradiated from objects such as buildings. A standard method of testing for distortion is to fly along the centre line of the runway and to record the output of the I.L.S. receiver. Such recordings, which on a perfect beam would be a straight line indicating constant zero signal, are frequently approximately sinusoidal in form and the tacit assumption has been made that the on-course line, or the zero signal line, follows a corresponding sinusoidal path in space. If in an aircraft on the centre line of the runway the I.L.S. indicator reads $\frac{1}{2}°$, it would appear reasonable to assume that the zero-line is $\frac{1}{2}°$ away. The assumption made, however, is that the sensitivity is not affected by the distortion and it is this assumption that is false. The true form of the zero-signal line has been obtained practically on several sites and simple theory supports the form found.

3.2. THE FORM OF I.L.S. DISTORTION

To find the true form of I.L.S. distortion it is necessary to obtain information over an area, rather than along a single line and this has been achieved by flying an aircraft along a series of tracks parallel to the centre line. To enable the pattern of the I.L.S. information to be drawn it is necessary to record the I.L.S. indications in the aircraft and simultaneously to record the aircraft position. Photographic means have been adopted for the work, the I.L.S. signal being recorded by a camera photographing a meter and position being obtained either from simultaneous photography of a series of carefully surveyed ground markers by a vertical camera in the aircraft, or by simultaneously photographing the aircraft with accurately sited ground cameras. By this means values of the I.L.S. signal at a large number of accurately determined positions are obtained. These can be entered on a map and a useful method of presenting the information is by drawing "contour" lines joining all points at which the I.L.S. information is the same. In the absence of distortion the contour map so obtained would be as shown in Fig. 5, but a practical result at R.A.F. Woodbridge is shown in Fig. 6, from which it will be seen that the zero-signal line is sawtoothed in shape. A simple theory based on a single reflecting object is given in Appendix I and a theoretical diagram based on this theory and using constants appropriate to R.A.F. Woodbridge appears at Fig. 7. The similarity between Figs. 6 and 7 is held to be

satisfactory. More complicated patterns have been found, notably at Filton, the contours for which appear in Fig. 8.

3.3. THE EFFECTS OF THE DISTORTION

In assessing the effects of this distortion it must be constantly borne in mind that the only positional information available to the aircraft on the approach is that provided by I.L.S. The problem in the aircraft is to reduce the I.L.S. signal to zero and maintain it there. In the presence of distortion this procedure will carry the aircraft away from the physical centre line until a point, such as *P* (Fig. 7), is reached where the aircraft is called upon to make an impossible change of direction, and confusion results. While the aircraft is following the I.L.S. zero signal path off to one side there is no information available from the I.L.S. system that the physical centre line of runway is not being followed. In principle, information of this departure is available from the heading of the aircraft and on this score it would appear that a heading stabilised control would, to some extent, ameliorate the effects of distortion.

A comparison of Figs. 5 and 7 shows immediately that the contours in general are close together on the distorted beam, thus indicating that the magnitude of the rate term is increased. A detailed study shows that over large areas the rate term is of incorrect sign, *i.e.* a lateral movement towards the beam causes an increase in I.L.S. signal and vice versa. A sketch of the areas in which this undesirable state holds on the beam described by Fig. 8 appears at Fig. 9. In these areas the rate of change of beam signal is a destabilising term and the theory behind the rate stabilised approach is no longer true. Some measure of the effect of distortion on a rate stabilised system is indicated by measurements taken in a Viking aircraft at R.A.F. Woodbridge. On a perfect beam obtained from an experimental system other than I.L.S., the standard deviation of lateral displacement from the centre line at a height of 200 ft. was only 17 feet, but on the I.L.S. system, distorted as shown in Fig. 6, this figure rose to over 50 ft.

A heading stabilised control should be affected by distortion much less than a rate stabilised system. A change of 10 microamps of localiser signal in a period of $\frac{1}{2}$ second, which is by no means uncommon, would theoretically demand a bank angle of only 1° using headings, but would call for 27° with rate. In practice such a large bank angle would be prohibited by a limiting system and the effects of the distortion correspondingly reduced, but this limiting cannot be carried too far as control in undistorted areas must still be effective.

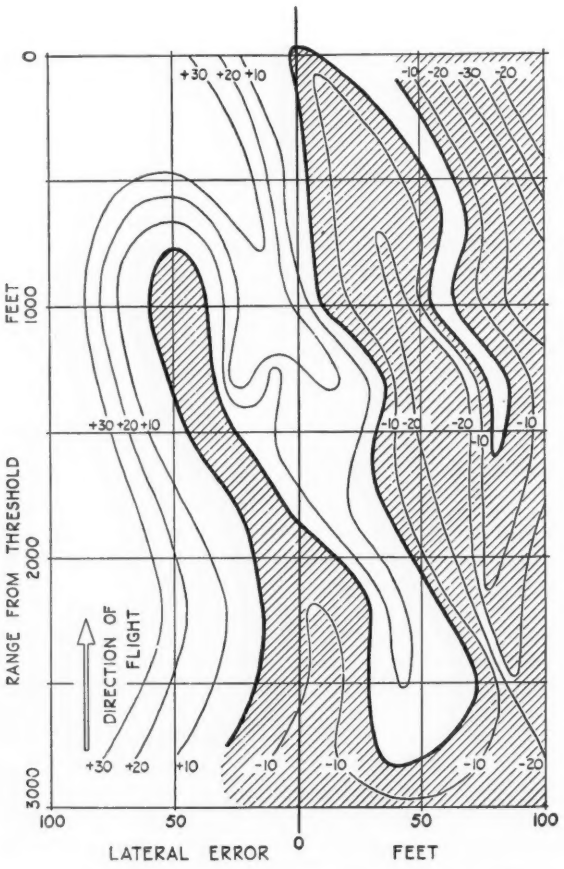

FIGURE 6. Practical beam contours—Woodbridge.

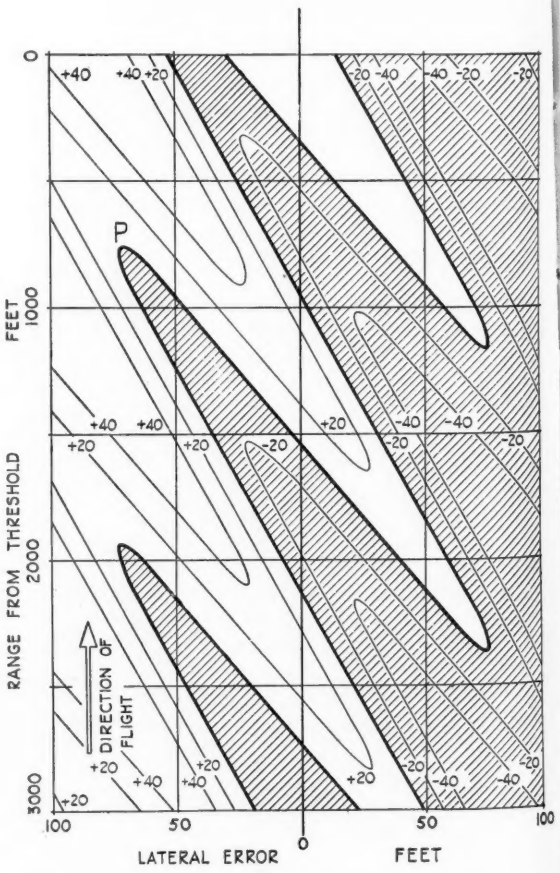

FIGURE 7. Theoretical beam contours—single reflecting objects.

Even with a bank angle limit of $\pm 5°$ a rate control is found to be very rough in distorted areas and, as will be seen later, comparatively ineffective in bringing the approach to a successful conclusion.

Up to the present time, contours have been obtained for nine beams. Of these nine, four—two at London Airport and two on R.A.F. airfields—were almost undistorted; four—two at Prestwick and two at the airfields used by the Experimental Unit—suffered from distortion to the degree shown in Fig. 6; and one—at Filton—was very badly distorted as shown in Fig. 8. This small survey indicates that distortion is quite liable to be met in practice and this is confirmed not only by pilot opinion, but also by data provided by the Civil Aeronautics Authority of the U.S.A. These data, although not in the form described here, indicate that distortion is liable to be met on American airfields to a similar degree. It is known that improvements to the linearity of beams can be made by reducing the coverage of the localiser information and thus to some extent preventing energy falling on re-radiating objects. This attack has been tried at the Blind Landing Experimental Unit and reduced the distortion considerably. Indeed the performance of a rate system was improved by this means to a stage where it was comparable to that of the competing heading system. The standard deviations of lateral displacement obtained on tests with a Devon aircraft were 55 ft. and 135 ft. for heading and rate stabilisation respectively, when all-round cover was used, the corresponding figures for the "narrow beam" system being 46 ft. and 43 ft.

The work described in this section caused the Experimental Unit to come down heavily on the side of heading stabilisation but the final touchstone had to be practical field trials. These are dealt with in the next section.

4. The Assessment of the Value of Approach Aids

4.1. INTRODUCTION

As I.L.S. is an established system and its susceptibility to site interference is unlikely to be eradicated, the problem facing the control engineer is not to produce the control system which will most closely follow perfect information, but to produce that system which will give the best performance on the imperfect information likely to be encountered. This criterion needs the establishment of a method of testing the overall system which, in turn, demands a close examination of the objective, *i.e.* a definition of a successful blind approach.

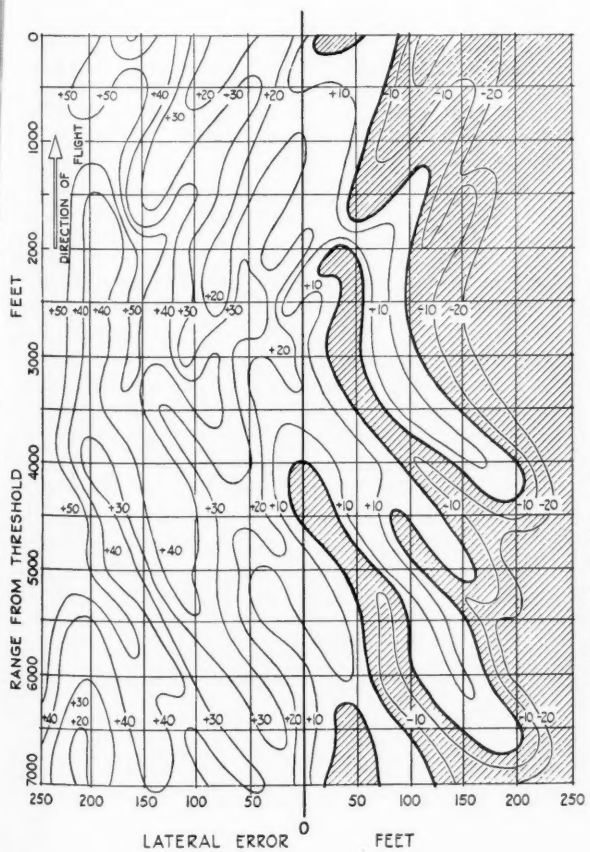

FIGURE 8. Practical beam contours—Filton.

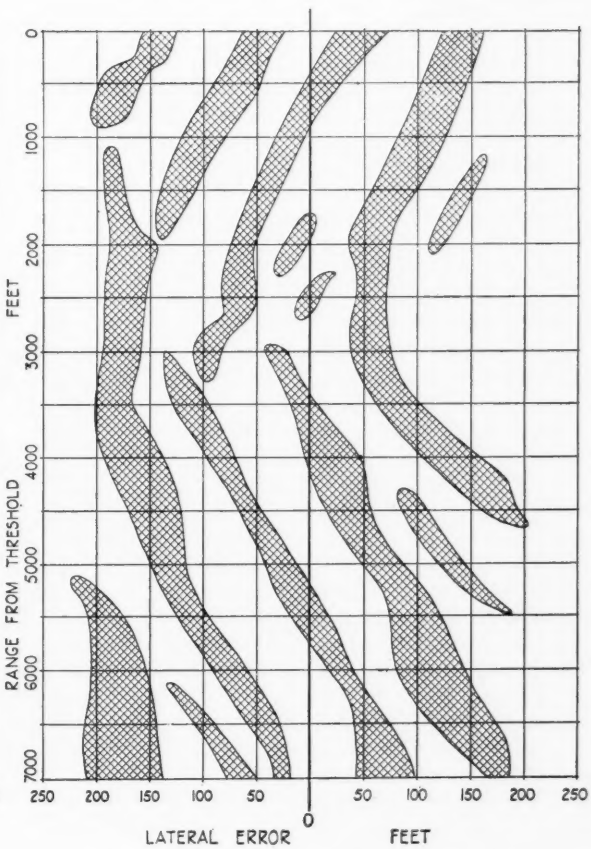

FIGURE 9. Filton—areas of reversed rate term.

4.2. THE CONCEPT OF A SUCCESSFUL APPROACH

An attempt to land under poor visual conditions using an instrument approach followed by a visual landing, may fail for many reasons, but not all the failures may be laid at the door of the approach system. The demand on the approach system is merely that it brings the aircraft into such a position and in such a configuration that, provided adequate visual information be available, a safe landing can be made. Whether or not a safe landing from any postulated initial conditions is possible, will depend solely on whether the manoeuvres called for are within the capabilities of the aircraft and are such that the pilot is prepared to make them. If both these conditions are fulfilled the approach may be said to be successful; if either fails, the approach is a failure. This concept of the success of an approach is here used as a basis of comparison of the competing systems, but obviously has far wider applications. It may be noted that the standard deviation of lateral displacement which has been used at various places in the paper is an inadequate measure of the "success" of a series of approaches, as it measures only the spread of aircraft position and takes no cognisance of the instantaneous lateral velocities. An approach which brings the aircraft on to the centre line of the runway, but tracking at right angles to it, could in no sense be called successful.

4.3. THE MATHEMATICAL FORMULATION OF THE CONCEPT

During the landing phase the motion of the aircraft has to be controlled in the horizontal plane to reduce any lateral error to an acceptable value and in the vertical plane to reduce the rate of descent for the landing. For the approaches considered in the paper it has been found that the glide path performance has been such that the azimuth control has invariably been the limiting factor. The pitch control has in every case been found to be satisfactory down to a height of 100 ft. or less and it is considered highly improbable that a pilot would be willing to proceed as low as this without adequate visual information. Accordingly the mathematical work has been confined to the azimuth case. There is a suspicion that with some future jet aircraft control on the glide path may fall below this standard in which case a similar formulation of success for the vertical plane would be required.

The requirements for putting the concept of a successful approach into quantitative form and thus formulating a "yardstick" with which to measure the success of approaches, are a specification of the allowable manoeuvres and a method of calculating for what initial conditions such limiting manoeuvres would not have to be exceeded for a landing to be made. The specification of limits for such parameters as bank angle and rate of roll is straightforward, as also is the

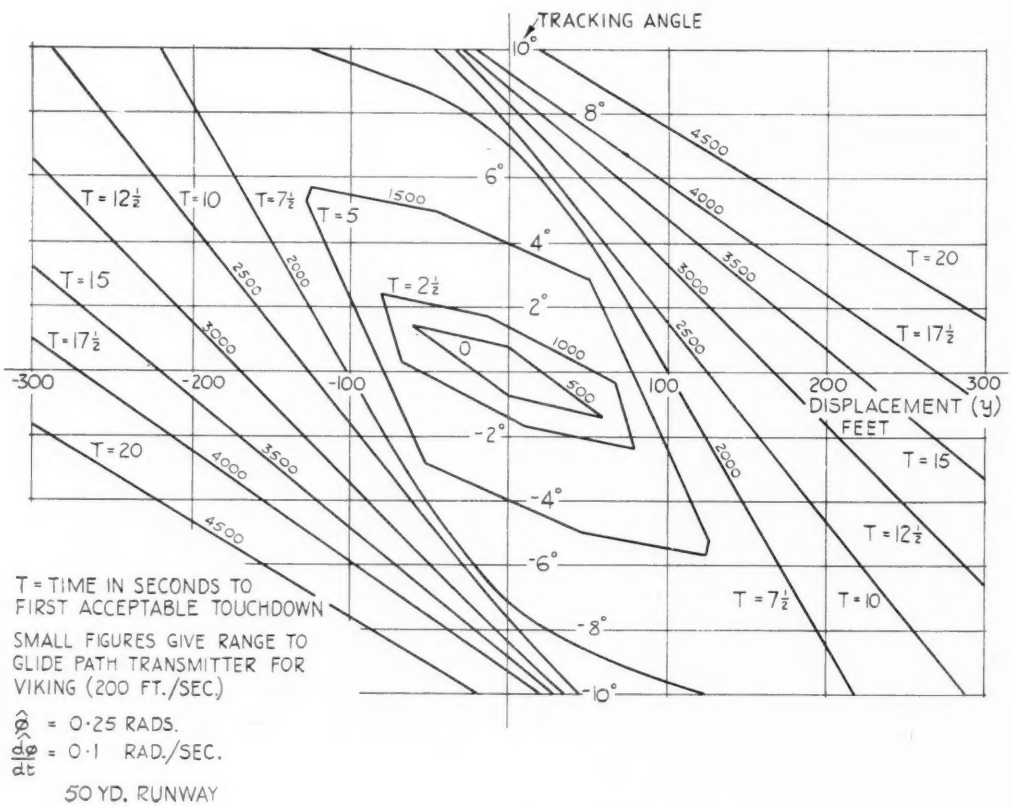

FIGURE 10. Approach success chart.

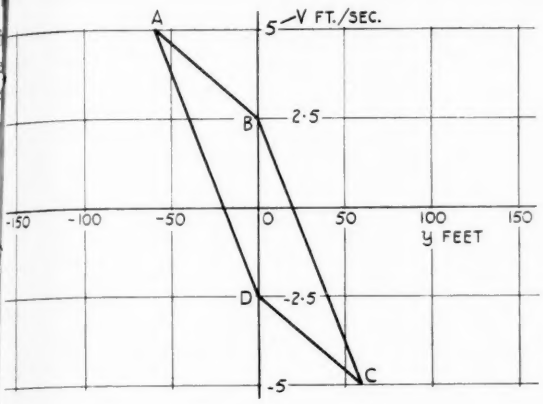

FIGURE 11. Assumed runway criterion.

specification of terminal conditions on the runway, but the determination of whether the limits would have to be exceeded requires a relatively simple formulation of the path of the aircraft, if the mathematical work is to be kept within bounds.

The detailed mathematical work is given in Appendix II, the method being basically as follows. The aircraft is assumed to be placed by the instrument approach a distance y_0 from the centre line with a lateral velocity V_0. As the bank angle on the approach is limited to a small value the bank at this critical stage is assumed to be zero. At touchdown the aircraft is required to have a small displacement y_1, a small tracking velocity V_1, zero bank and zero rate of roll. The manoeuvre connecting these initial and final states is assumed to be of the form

$$y = a_0 + a_1 t + a_2 t^2 + a_3 t^3 + a_4 t^4 + a_5 t^5 + a_6 t^6$$

so that for every set of initial conditions there will be a unique path of this form. Such paths are treated as tolerable if the bank does not exceed a certain angle nor the rate of roll exceed a specified limit, but unacceptable if either criterion is violated. The results are well displayed in the form of charts—known to the Experimental Unit as Approach Success Charts—such as Fig. 10, in which acceptable combinations of initial displacement and lateral velocity at any range are those represented by points lying within the appropriate locus.

The method of calculation given in Appendix II will be seen to be a simple routine based on universal curves and it is applicable to any values of limiting criteria desired. Following discussion with many pilots the criteria used by the Blind Landing Experimental Unit for Viking and Varsity aircraft have been

Max. bank angle 0·25 radian (approximately 14°)

Max. rate of roll 0·1 rad./sec. (approximately $5\frac{1}{2}$°/sec.)

Touchdown limits as shown in Fig. 11. (This assumes a 50 yd. wide runway.)

Fig. 12 is included to illustrate the effects of increasing the allowable rate of roll, and of assuming a 100 yard wide runway.

It should be noted that original work in this field was conducted by the Sperry Gyroscope Co., U.S.A.[6] Their work was based on a different mathematical expression but lacked adequate flexibility. The present formulation agrees closely with theirs in the one case they considered, but the labour in dealing with new cases by their method was held to be prohibitive.

4.4. THE ASSESSMENT TECHNIQUE

To obtain a reasonably representative sample a set of about 50 approaches is required for each test. Every approach must be fully recorded and this has been done photographically, either by using a vertical camera in the aircraft to photograph accurately positioned ground markers or, by using accurately sited ground cameras to photograph the aircraft. By this means graphs of lateral displacement, range and height can be plotted against time. The lateral displacement at any chosen range may be readily determined from these graphs, as also can the lateral velocity from the slope of the displacement graph. These two values are entered on the approach success diagram appropriate to the aircraft concerned and the range being considered, and if the point lies in the "acceptable" area the approach is considered successful at that range. This process is continued for all the set of approaches and for all ranges of interest and a figure for each range of percentage approach success is readily derived. It is submitted that this figure affords a good relative measure of the value of approach systems.

One further advance is possible. The set of points obtained from a trial may be viewed as a sample of an infinite population and, provided that the distribution of both lateral displacement and lateral velocity approximates to normal, statistical techniques exist for estimating the parameters of the infinite distribution. A set of points obtained on a good site with a heading stabilised control is shown in Fig. 13, together with ellipses indicating the form of the estimated infinite population. The amount of this distribution lying outside the acceptable limits may readily be calculated and this figure may prove to be an even better measure of success.

4.5. THE RESULTS

During the automatic approach work over 3,000 recorded approaches have been made and the presentation of all these results would overburden the paper. The results of a series of tests conducted at a number of sites, using a Viking aircraft, are shown in Tables I and II, which also include the standard deviation of the height at each range to give some measure of the accuracy of the glide path control. A 50 yard runway has been assumed throughout, although at three airfields (London, Prestwick and Filton) the instrument runway is 100 yards wide. A separate analysis of the results on these sites indicated that 100 per cent. success was achieved in all cases down to a nominal height of 100 feet when flying on the glide path.

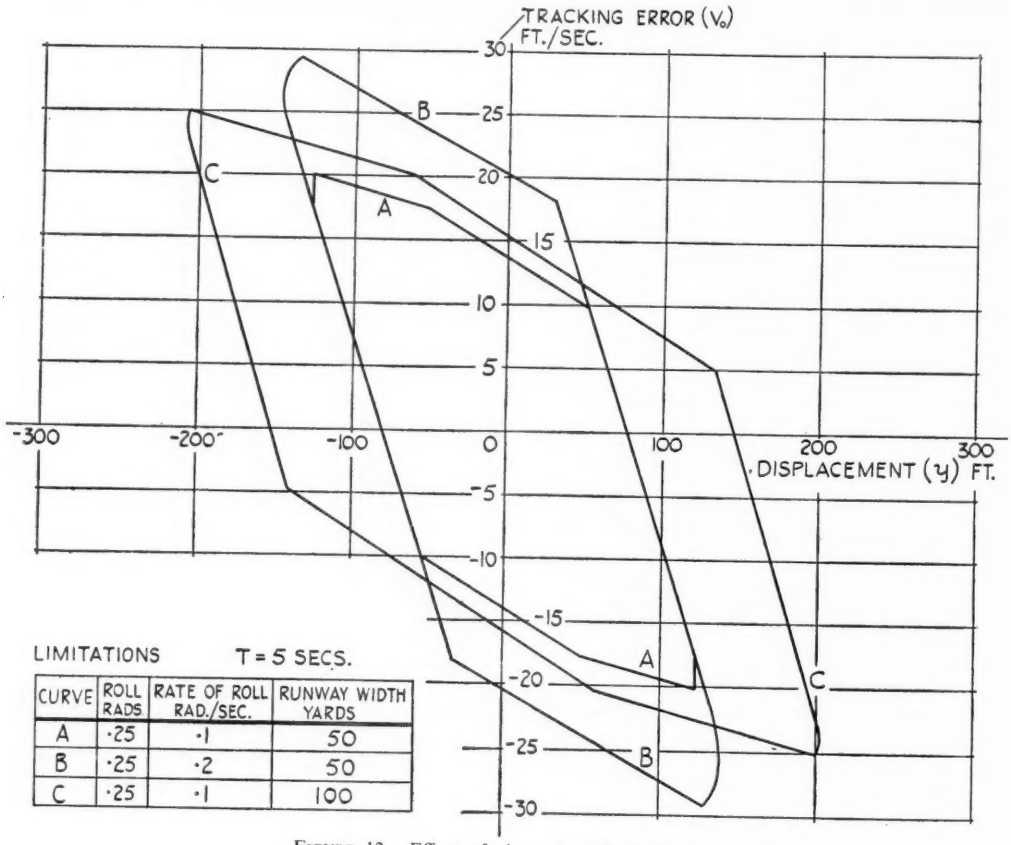

FIGURE 12. Effect of changes of limitations.

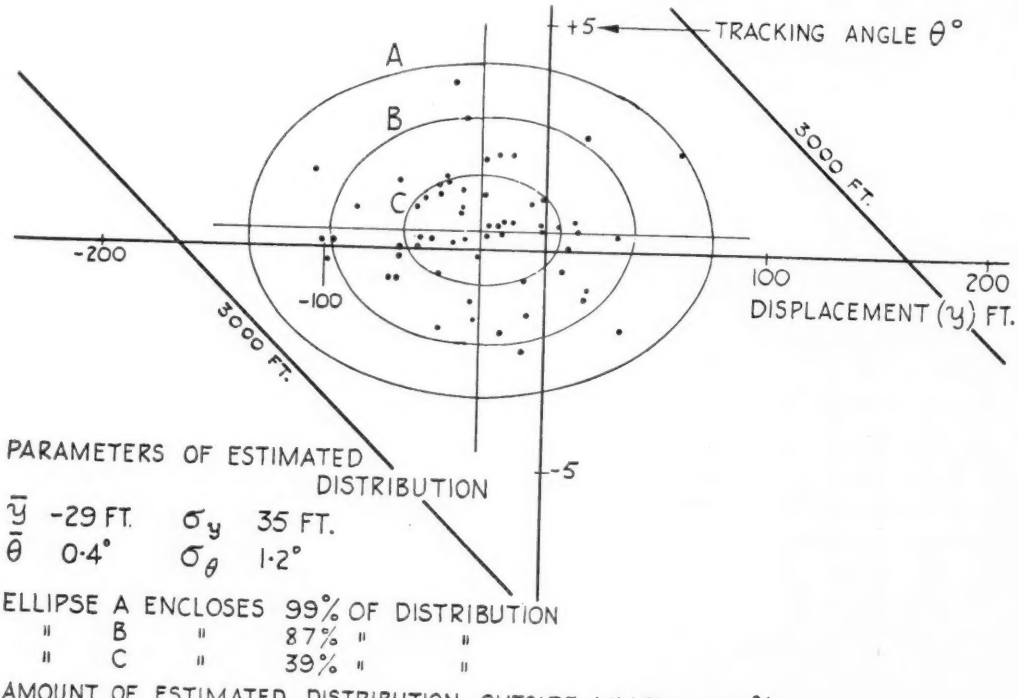

FIGURE 13. Typical estimated infinite distribution.

4.6. DISCUSSION OF THE RESULTS

Of the three airfields covered by Table I, R.A.F. Great Massingham had a beam which was virtually undistorted, R.A.F. Martlesham Heath exhibited "average" distortion and Filton was gravely distorted (Fig. 8). The performance of the heading stabilised system is seen to be similar at all three sites, but the rate stabilised system reached the same level only at R.A.F. Great Massingham. At Martlesham Heath it was markedly inferior and at Filton tests had to be abandoned after eight runs as on each of these runs the aircraft was put outside the coverage of the ground cameras (± 600 ft., 3,000 ft. from the glide path). As a result of these tests the decision was taken to concentrate on the performance of the heading stabilised system and further results on this system are given in Table II. Of the sites chosen for this table both the London runways were free from distortion while the distortion exhibited at Prestwick could be classed as "average."

It should be noted that no special action was taken on any of the sites before the recordings were taken and no adjustments for differences have been made afterwards, even though it is apparent from Fig. 8 that during the trials at Filton the beam was not coincident with the physical centre line of the runway, and at London the combination of the beams as set up by the Ministry of Civil Aviation and the airborne receiver adjusted at the Blind Landing Experimental Unit was found to give signals of reduced sensitivity. The trials were not delayed by weather, except for a short period at London during which the wind was in such a direction that Air Traffic Control found it impossible to fit in the experimental flying against the scheduled traffic. The trials may therefore be taken as giving a representative picture of the performance likely to be achieved by heading stabilised automatic approach equipment in practice and on the basis of these trials the design of a production automatic pilot using heading stabilisation has been finalised.

The performance in pitch needs little comment—it is uniformly adequate down to 100 ft.

5. Non-automatic I.L.S. Approaches

A heavy responsibility for the safety of his aircraft falls on a pilot at all stages of flight but at no stage is this burden heavier than during the approach and landing manoeuvre, when the aircraft is being flown at low air speed near the ground, where the consequences of an error of judgment are most likely to prove disastrous.

Under blind conditions he is called upon to perform a dual function—the "active" function of flying his aircraft with the high precision called for on an instrument approach and a "monitoring" function not only of ensuring that the aircraft at any instant is in a safe configuration, but also of maintaining a continual appreciation of the position and path of the aircraft, so that the transition from instrument to visual flight required at the end of the approach can be made smoothly. There can be little doubt that these requirements tax even the most highly skilled pilot severely, probably to such an extent that the margin of safety over human failure is small and it is apparent that means of

TABLE I

COMPARISONS BETWEEN HEADING AND RATE STABILISED APPROACHES

R.A.F. Martlesham Heath

Range from G.P.	*% Approach Heading*	*Success Rate*	*Height feet Mean*	*S.D.*
5,000	100	96	339	19
4,500	100	96	302	17
4,000	100	96	267	15
3,500	100	89	234	14
3,000	100	67	197	12
2,500	97	33	163	8
2,000	69	7	131	4
1,500	54	4	98	5
1,000	28	4	66	4

R.A.F. Great Massingham

Range from G.P.	*% Approach Heading*	*Success Rate*	*Height feet Mean*	*S.D.*
3,500	100	100	166	6
3,000	100	100	146	6
2,500	100	100	112	6
2,000	98	94	93	7
1,500	93	94	70	6
1,000	64	66	48	5

Filton

Range from G.P.	*% Approach Heading*	*Success Rate*	*Height feet Mean*	*S.D.*
3,500	100	Abandoned	161	7
3,000	94		135	6
2,500	91		112	6
2,000	71		92	7
1,500	54		69	9
1,000	29		—	—

TABLE II

FURTHER APPROACH SUCCESS RESULTS—HEADING STABILISATION

London—Runway 28 Left

Range from G.P. (ft.)	*% Approach Success*	*Height (ft.) Mean*	*S.D.*
3,500	100	189	6
3,000	100	163	5
2,500	98	136	5
2,000	90	109	5
1,500	71	81	6

London—Runway 10 Right

Range from G.P. (ft.)	*% Approach Success*	*Height (ft.) Mean*	*S.D.*
3,500	100	192	5
3,000	100	166	5
2,500	100	140	6
2,000	92	109	8
1,500	74	74	7

Prestwick

Range from G.P. (ft.)	*% Approach Success*	*Height (ft.) Mean*	*S.D.*
3,500	100	187	6
3,000	100	159	4
2,500	97	132	5
2,000	89	105	7
1,500	74	75	7

easing the load must be found. Where two pilots are carried, it is possible to divide the duties between them, one possibility being that the co-pilot concentrates on the instrument flying leaving the captain free to concentrate on the monitoring duties. An extension of this suggestion is the fitting of automatic equipment as used in the tests described in this paper. This course would undoubtedly lead to a reduction in the load on the pilot as he would be left completely free to monitor the approach, apart from the task of maintaining the air speed at the required value. Moreover it is believed that by the use of automatic equipment approaches of the greatest possible accuracy would be obtained.

While there is a clear technical case for the fitting of automatic approach equipment to an aircraft, economic considerations must also apply and if the decision be taken to rely on manual flying for I.L.S. approaches, some other means of relieving the load on the pilot must be sought. In the absence of automatic equipment not only does the actual control of the aircraft revert to the pilot but, more important, the mental load of computing the exact path to follow. This computational problem is exactly that already considered and the quantitative results obtained have a direct bearing on this aspect of the pilot's task.

A pilot knows well that if he attempts to control the aircraft by applying bank directly proportional to the I.L.S. indication, the aircraft will oscillate violently about the true path and the approach will be a failure. This is exactly parallel to the automatic case and the solution lies in determining some measure of the velocity of approach to the beam centre, so that a stable approach may be achieved. A stabilising term closely akin to the rate-term considered for automatic approach is available direct from the I.L.S. indicator, the rate of swing of the needle being a measure of the differential of the beam signal which, on a perfect beam, is proportional to the rate of closing the centre-line. It has been seen, however (Section 3.3), that in the presence of beam distortion this differential is far from being a true measure of the required quantity, being not only of the wrong magnitude but frequently reversed in sign and thus becoming a destabilising, rather than a stabilising, term. The pilot cannot therefore rely on good performance using this technique, which in any case would require an almost continuous watch on the I.L.S. instrument, to the detriment of the "monitoring" function.

The alternative source of a stabilising term is the heading and this is used in differing degrees by many pilots who have learned its value by experience. A common method is for the pilot to turn on to a chosen heading and, when the aircraft has settled down, to select a new heading in accordance with the indication given him by the I.L.S. A few cycles of this technique, for which adequate time must be allowed by the operational procedure, results in the aircraft being brought stably near the centre line and further corrections are made in a similar manner if the I.L.S. meter indicates departure from the beam zero-signal line. This solution too calls for mental calculation, particularly as in the presence of a changing crosswind the heading required to track along the centre line is continuously changing.

It is apparent that the pilot could be relieved of these mental calculations if the required heading could be calculated for him. This is done in the Ground Controlled Approach system and may well account for the liking many pilots have for that system. In the I.L.S. case the calculation would be required to be performed automatically and the result presented on some form of meter. If the requirement be maintained that the aircraft be held to the zero-signal line at all times, the calculation would require a precise knowledge of the crosswind at all heights. This information is not available and it may be noted that up to the present pilots have been asked to make mental calculations on insufficient information, so that they have been thrown back on "cut and try" methods, thus reducing still further the mental effort available for the monitoring task.

In the automatic approach work (Section 2.2.2), the requirement for holding the zero signal line far out was abandoned and the "correct" heading at any range was found to be that heading which satisfies the equation

$$\sigma - K_4(\psi - \psi_0) = 0.$$

A possible method of presentation would be to display the quantity on the left hand side of this equation on a centre-zero meter and instruct the pilot to maintain this meter at zero. His method of doing this would be to apply bank in direct proportion to the deflection of the meter and a neat method of ensuring this is to present to the pilot the quantity

$$\phi - K_1[\sigma - K_2(\psi - \psi_0)]$$

so that if this quantity be held to zero the pilot is not only at any instant aiming at the "correct" heading, but also applying the most suitable bank to get on to that heading after any disturbance. The Sperry Zero Reader is, of course, such an instrument, and similar devices have been marketed by other manufacturers. It is beyond the scope of the paper to discuss the relative engineering merits of the various products.

Any means of adopting the principle, however, should ease the load and moreover, lead inherently to more accurate approaches. The degree of easement will depend upon the amount of concentration on this instrument demanded from the pilot, but it may be noted that if an error builds up in a period during which the pilot is attending to other matters, the system will give an immediate indication of the correct remedial action that should be taken. Quantitative tests of a "Zero Reader" are currently being conducted at the Blind Landing Experimental Unit and early results show promise in that they indicate that the potential accuracy, as measured by the methods outlined in this paper, comes close to that obtained in the automatic case. The final assessment of the value of such aids to manual flying, however, must come from their use under actual operational conditions, as complete simulation of these conditions may well be unobtainable. To ensure a fair test of accuracy it is essential that the pilot under test be denied any possibility of obtaining visual or other extraneous information, but this in turn demands the carrying of a safety pilot who thereby relieves the pilot under test of the full responsibility for the safety of the aircraft. Despite this limitation the results should still prove of great value,

and it is intended to extend the work to the case of the aircraft being flown manually by a pilot using only the I.L.S. indicator in conjunction with a standard blind flying panel.

6. Concluding Remarks

It is claimed that the work described in this paper has placed the technical problems of the approach phase on a firm quantitative basis, with the reservation that the work has dealt almost exclusively with piston-engined aircraft. New technical problems must undoubtedly be faced in the extension to jet aircraft of the results obtained. These problems would appear to arise because of the very different drag characteristics of these aircraft. It is not expected that performance in the horizontal plane will be markedly different from that obtained with piston-engined aircraft, but in the vertical plane difficulties may be expected to arise from the speed demanded on the approach, if accurate stable following of the glide path is to be achieved using attitude control and to the lower deceleration available in the last stages. These two effects both tend to increase the height at which the instrument approach must be discontinued if landings are to be made with safety and thus reduce the degree to which adverse weather conditions will be defeated. A study of throttle control during the approach, with the object of reducing the approach speed demanded, might well prove advantageous.

The technical problems of the approach phase, however, are only part of the overall problem. It is becoming increasingly realised that the problems of the transition from instrument to visual flight are probably the most important of all the problems involved in the approach and landing manoeuvre. The study of this transition phase calls for work in the fields of instrument approach, lighting, meteorology, aerodynamics, and psychology and advances will only be made by concerted work by experts in these respective fields in association with practising pilots. Some work has been done along these lines and it is the author's hope that at some later date he will be allowed to collaborate with other workers and present a paper on this important subject. The present paper should be viewed as an attempt to clear some of the ground leading towards that objective.

ACKNOWLEDGMENTS

Every member of the Blind Landing Experimental Unit, past or present, has at some stage made contributions to this work and the author should be viewed only as the member of that Unit to whom fell the task of presenting it to the Society. He must, however, remain responsible for all opinions expressed and they must not be assumed necessarily to represent those of the Unit, the Royal Aircraft Establishment of which that Unit is an outstation, or the Ministry of Supply. Acknowledgment is made to the Chief Scientist, Ministry of Supply, for permission to publish this paper.

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APPENDIX I

THE FORM OF I.L.S. BEAM BENDS—A SIMPLE THEORY

1. The Mechanism

In Fig. 14 consider an aircraft at P on the centre line of an I.L.S. localiser situated at T. Let the "left" and "right" patterns (Fig. 1*a*) be represented by $F(\sigma)$ and $f(\sigma)$ respectively. The fields at P due to the two patterns may be written $EF(0)$ and $Ef(0)$ and these will be equal.

Let R be a re-radiating object. Additional fields caused by energy which has traversed the path TRP will be received at P and, writing η for the ratio of the indirect and direct fields at P if the course at T were omni-directional, the "left" and "right" fields at P are readily seen to be the vector sums of $EF(0)$ and $E\eta F(\phi)$, and $Ef(0)$ and $E\eta f(\phi)$ respectively. In general η will be much smaller than one and the magnitude of the resultant fields may be taken as

$$EF(0)+E\eta F(\phi)\cos\alpha \quad \text{and} \quad Ef(0)+E\eta f(\phi)\cos\alpha$$

where α is the phase angle between the direct and indirect fields.

In general these magnitudes will be different and although the aircraft is on the centre line the indicator will read a small angle ε given by

$$E\eta\,[F(\phi)-f(\phi)]\cos\alpha = E\,[F(\varepsilon)-f(\varepsilon)]$$

Over the linear portion of the localiser coverage the quantity $F(\varepsilon)-f(\varepsilon)$ is a linear function of the angle ε and writing

$$F(\varepsilon)-f(\varepsilon)=KF(0)\,\varepsilon,$$

$$\varepsilon=\frac{\eta}{K}\left[\frac{F(\phi)-f(\phi)}{F(0)}\right]\cos\alpha.$$

The quantity in square brackets is a function of the position of the re-radiating object, K is a constant of the system and η over a small area can be treated as constant, even though the polar diagram of the re-radiation be complex. The error may thus be expressed in the form

$$\varepsilon=\hat{\varepsilon}\cos\alpha$$

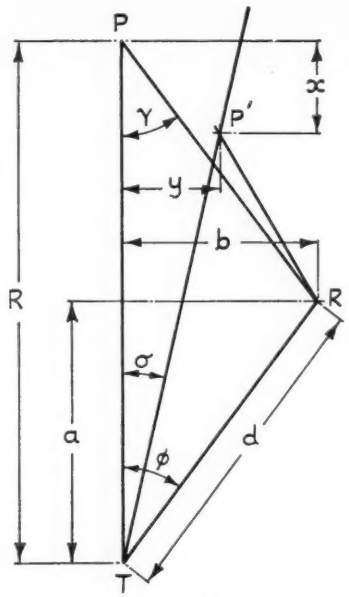


FIGURE 14.

the indication at the more general point off the centre line being readily seen to be

$$I=\sigma+\hat{\varepsilon}\cos\alpha.$$

2. Path Difference as a Function of Aircraft Position

To study the form of a beam bend it is necessary to consider the change of path length and hence of the angle α with the movement of P'. In Fig. 14 the path difference between the indirect path TRP' and the direct path TP' is

$$d+\{(R-a-x)^2+(b-y)^2\}^{\frac{1}{2}}-\{(R-x)^2+y^2\}^{\frac{1}{2}}$$

while the path difference for the point P is given by

$$d+\{(R-a)^2+b^2\}^{\frac{1}{2}}-R.$$

The change in path length Δl in moving from P to P' is the difference between these two quantities which on the assumption that $x \ll R$ and $y \ll R$, reduces to

$$\Delta l=\frac{-by}{\{(R-a)^2+b^2\}^{\frac{1}{2}}}-\frac{(R-a)x}{\{(R-a)^2+b^2\}^{\frac{1}{2}}}+x$$

or if the angle TPR is written γ,

$$\Delta l=x(1-\cos\gamma)-y\sin\gamma$$

and thus the phase difference $=\frac{2\pi}{\lambda}[x(1-\cos\gamma)-y\sin\gamma]$

where λ is the wavelength, provided that the point P be chosen such that the indirect field leads the direct field by 90°. There is little loss in generality in this assumption.

3. The Equation for the Contours

The indication at any point P' will be given by

$$I=\sigma+\hat{\varepsilon}\sin\frac{2\pi}{\lambda}[x(1-\cos\gamma)-y\sin\gamma] \quad \text{where } \sigma=y/R.$$

It is convenient to express this equation in a slightly different form. It will be noted that if y be held constant, *i.e.* the aircraft is flown parallel to the centre line, the error will vary sinusoidally with wavelength X given by $X=\lambda/1-\cos\gamma$ and similarly if the beam be cut at 90° a "ripple" wavelength Y equal to $\lambda/\sin\gamma$ will be observed. Using these parameters, the equation for the angular indication over a small area becomes

$$I=y/R+\hat{\varepsilon}\sin 2\pi\left(\frac{x}{X}-\frac{y}{Y}\right).$$

APPENDIX II

THE MATHEMATICAL FORMULATION OF APPROACH SUCCESS

1. Determination of the Path for any Initial Conditions

It is assumed that the path of the aircraft between time $t=0$ and time $t=T$ is given by a polynomial of the form

$$y=a_0+a_1t+a_2t^2+a_3t^3+a_4t^4+a_5t^5+a_6t^6 \quad . \quad (1)$$

If at $t=0$, $y=y_0$, $\frac{dy}{dt}=V_0$

$$a_0=y_0 \text{ and } a_1=V_0 .$$

Furthermore, as the initial bank is assumed to be always zero, there is to be no initial lateral acceleration so that $\frac{d^2y}{dt^2}=0$ at $t=0$,

i.e. $a_2=0$.

Inserting these values the sextic becomes

$$y=y_0+V_0t+a_3t^3+a_4t^4+a_5t^5+a_6t^6 \quad . \quad (2)$$

It is convenient at this stage to introduce a new parameter

$$x=\frac{t}{T} \quad . \quad . \quad . \quad . \quad (3)$$

giving

$$y=y_0+V_0Tx+a_3T^3x^3+a_4T^4x^4+a_5T^5x^5+a_6T^6x^6$$

which is more conveniently written

$$y=y_0+V_0Tx+Ax^3+Bx^4+Cx^5+Dx^6 \quad . \quad (4)$$

where

$$A=a_3T^3 \quad . \quad . \quad . \quad (5)$$
$$B=a_4T^4 \quad . \quad . \quad . \quad (6)$$
$$C=a_5T^5 \quad . \quad . \quad . \quad (7)$$
$$D=a_6T^6 \quad . \quad . \quad . \quad (8)$$

From equation (4), noting that $\frac{d^n}{dx^n}=\frac{T^nd^n}{dt^n}$. (9)

we have

$$y=y_0+V_0Tx+Ax^3+Bx^4+Cx^5+Dx^6$$

$$\frac{dy}{dx} = T\frac{dy}{dt} = V_0T + 3Ax^2 + 4Bx^3 + 5Cx^4 + 6Dx^5 \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (10)$$

$$\frac{d^2y}{dx^2} = T^2\frac{d^2y}{dt^2} = 6Ax + 12Bx^2 + 20Cx^3 + 30Dx^4 \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (11)$$

$$\frac{d^3y}{dx^3} = T^3\frac{d^3y}{dt^3} = 6A + 24Bx + 60Cx^2 + 120Dx^3 \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (12)$$

$$\frac{d^4y}{dx^4} = T^4\frac{d^4y}{dt^4} = 24B + 120Cx + 360Dx^2 \quad . \quad . \quad (13)$$

If at $x=1$ ($t=T$) it is stipulated that $y=y_1$ $dy/dt=V_1$, roll$=0$ (*i.e.* $d^2y/dt^2=0$) and that rate of roll$=0$ (*i.e.* $d^3y/dt^3=0$), the unknown constants may be obtained from the equations:—

$$A+B+C+D = y_1 - y_0 - V_0T$$
$$3A+4B+5C+6D = -V_0T + V_1T$$
$$6A+12B+20C+30D = 0$$
$$6A+24B+60C+120D = 0$$

To ease the computing it has been found convenient to introduce the further parameters

$$Z = (V_0 - V_1)T \quad . \quad . \quad . \quad (14)$$
$$Y = (y_0 - y_1 + V_1T) \quad . \quad . \quad (15)$$

The four simultaneous equations to give A, B, C and D then become in their lowest terms

$$A+B+C+D = -Y-Z \quad . \quad . \quad (16)$$
$$3A+4B+5C+6D = -Z \quad . \quad . \quad (17)$$
$$3A+6B+10C+15D = 0 \quad . \quad . \quad (18)$$
$$A+4B+10C+20D = 0. \quad . \quad . \quad (19)$$

The solutions are

$$A = -20Y - 10Z \quad . \quad . \quad . \quad (20)$$
$$B = 45Y + 20Z \quad . \quad . \quad . \quad (21)$$
$$C = -36Y - 15Z \quad . \quad . \quad . \quad (22)$$
$$D = 10Y + 4Z. \quad . \quad . \quad . \quad (23)$$

These are the coefficients of the sextic in parametric form (equation (4)), the relationship between these values and the coefficients of the original sextic (equation (1)) being given by equations (5) to (8).

2. Calculation of the Universal Curves

2.1. MAXIMUM RATE OF ROLL

If an aircraft is put into a perfectly banked turn, the angle of roll being ϕ, the lateral acceleration produced is given by $g\tan\phi$. If the track of the aircraft is at angle ψ to the centre line of the runway, the acceleration at right angles to the runway will be given by

$$\frac{d^2y}{dt^2} = g\tan\phi\cos\psi.$$

In general the angles will be sufficiently small for the approximation

$$\frac{d^2y}{dt^2} = g\phi \quad . \quad . \quad (24)$$

to be made, giving

$$\phi = \frac{1}{g}\frac{d^2y}{dt^2} = \frac{1}{gT^2}\frac{d^2y}{dx^2}. \quad . \quad . \quad (25)$$

Differentiating this equation gives an expression for the rate of roll in terms of the parameters previously used, *i.e.*

$$\frac{d\phi}{dt} = \frac{1}{g}\frac{d^3y}{dt^3} = \frac{1}{gT^3}\frac{d^3y}{dx^3}. \quad . \quad . \quad (26)$$

indicating that peak values of $d\phi/dt$ will correspond to peak values of d^3y/dx^3, *i.e.* to values of x such that $d^4y/dx^4=0$.

These values of x are given by equation (13) which in its lowest terms is

$$15Dx^2 + 5Cx + B = 0.$$

The values are

$$x_1, x_2 = -\frac{C}{6D} \pm \left\{\left(\frac{C}{6D}\right)^2 - \frac{B}{15D}\right\}^{\frac{1}{2}} \quad . \quad (27)$$

The peak values of d^3y/dx^3 are given by inserting x_1 and x_2 in turn in equation (12), but it may be noted that any value of x outside the range $x=0$ to $x=1$ will not be appropriate to the problem. Alternatively the values found, while mathematical maxima (minima), may not necessarily be the largest values called for in the range and it is necessary to derive the value of d^3y/dx^3 at $x=0$ also. It is simply $6A$, from equation (12).

2.2. MAXIMUM BANK ANGLE

The connection between bank angle and the parameters used is given by equation (25), *i.e.*

$$\phi = \frac{1}{g}\frac{d^2y}{dt^2} = \frac{1}{gT^2}\frac{d^2y}{dx^2}$$

and the stationary values of ϕ will correspond to the stationary values of d^2y/dx^2. These will occur at values of x given by $d^3y/dx^3=0$, *i.e.*

$$6A + 24Bx + 60Cx^2 + 120Dx^3 = 0.$$

It is however unnecessary to solve the cubic as one of the terminal conditions is that d^3y/dx^3 should equal 0 at $x=1$. Dividing the equation by $(1-x)$ and using the relationship of equation (19) gives the new equation

$$A + (A+4B)x - 20Dx^2 = 0 \quad . \quad . \quad (28)$$

which gives

$$x_3, x_4 = \frac{E}{40D} \pm \left\{\left(\frac{E}{40D}\right)^2 + \frac{A}{20D}\right\}^{\frac{1}{2}} \quad . \quad (29)$$

where

$$E = A + 4B \quad . \quad . \quad . \quad (30)$$

The peak values of d^2y/dx^2 are given by inserting x_3 and x_4 in turn in equation (11). Once again interest is confined to the range $x=0$ to $x=1$ and any value of x outside this range will not be appropriate to the problem. The values found are the largest values in the range as the initial and final values are both zero.

2.3. THE UNIVERSAL CURVES

The four coefficients A, B, C and D are all of the form $lY+mZ$ and therefore the expressions for the maximum rates of roll, the initial rate of roll, and the maximum bank angles are all homogeneous functions of Y and Z. The results may therefore be expressed in a single curve for each, rather than having to attempt to present the information in families of curves. This has been achieved by plotting the quantities

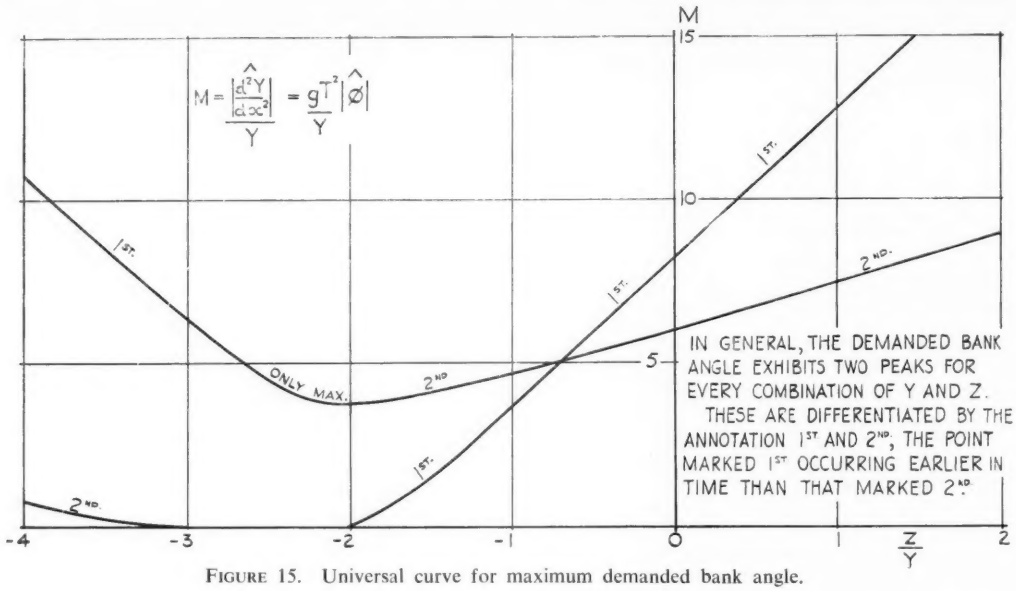


FIGURE 15. Universal curve for maximum demanded bank angle.

$$M = \frac{1}{Y}\left|\frac{d^2\hat{y}}{dx^2}\right| = \frac{gT^2}{Y}\left|\hat{\phi}\right|$$

and

$$N = \frac{1}{Y}\left|\frac{d^3\hat{y}}{dx^3}\right| = \frac{gT^3}{Y}\left|\frac{d\hat{\phi}}{dt}\right|$$

against Z/Y. These universal curves appear as Figs. 15 and 16.

3. Production of Charts for Specific Cases

3.1. LIMITATIONS TO BE IMPOSED

The production of charts for practical use requires decisions on the maximum bank and maximum rate of roll that are to be allowed, on where the manoeuvre is to be assumed to end and on the tolerances allowed at the end of the manoeuvre. There is complete freedom of choice of the values to be assigned to all these quantities, but reasonable values for a Viking aircraft adopted by the Blind Landing Experimental Unit are:

Maximum bank angle	$\lvert\hat{\phi}\rvert$ 0·25 rads.
Maximum rate of roll	$\left\lvert\frac{d\hat{\phi}}{dt}\right\rvert$ 0·1 rad./sec.
End of manoeuvre	500 ft. upwind from threshold
Runway tolerances	as shown in Fig. 11.

The work of producing the charts proceeds in three stages and a specific example for $T = 20$ seconds, using the limitations already given, will be used to illustrate the details of the method.

3.2. STAGE 1—DETERMINATION OF LIMITING Y AND Z

Inserting the specific values of $\hat{\phi}$, $d\hat{\phi}/dt$ and T in the general formulae for M and N gives immediately

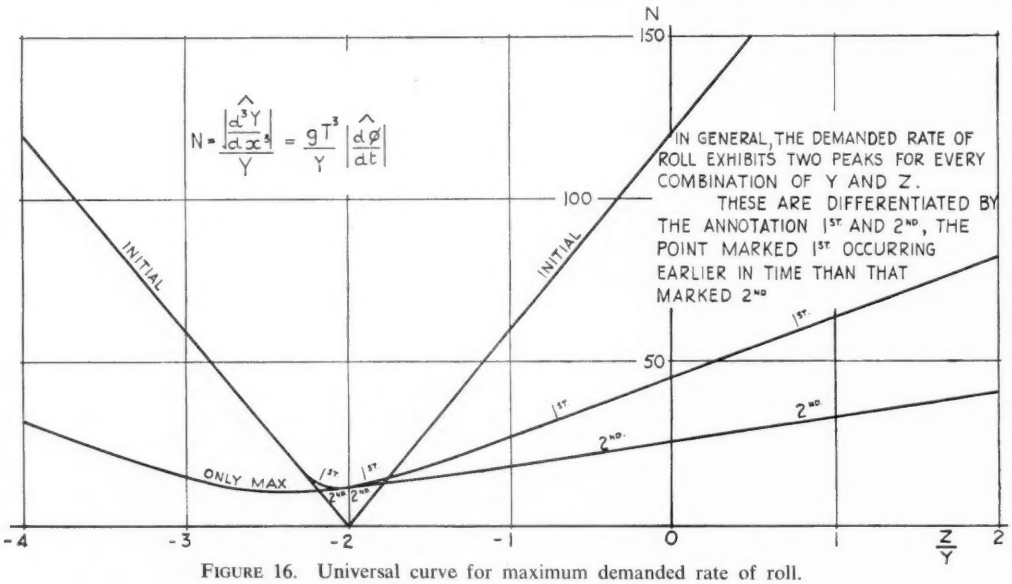


FIGURE 16. Universal curve for maximum demanded rate of roll.

$$M = \frac{gT^2\hat{\phi}}{Y} = \frac{32{\cdot}2 \times 400 \times 0{\cdot}25}{Y} = \frac{3{,}220}{Y}$$

$$N = \frac{gT^3}{Y}\frac{d\hat{\phi}}{dt} = \frac{32{\cdot}2 \times 8{,}000 \times 0{\cdot}1}{Y} = \frac{25{,}760}{Y}$$

and thus any value of M in Fig. 15 or N in Fig. 16 corresponds to a particular value of Y. The corresponding value of Z/Y is also obtainable from the curves so that both Y and Z at any limiting point may readily be calculated. The work has been reduced to a routine by the computing sheet of Fig. 17 which is extended to give further associated quantities y_0' and V_0'. These arise as follows:—

The equations for Y and Z may be rearranged to give

$$y_0 = Y + (y_1 - V_1 T)$$
$$V_0 = Z/T + (V_1)$$

and if no tolerance were allowed at touchdown, *i.e.* the aircraft were required to be exactly on the centre line tracking exactly along it, the quantities in brackets in these equations would both be zero. The special values of y_0 and V_0 in these circumstances will be referred to as y_0' and V_0' and it is these values which are plotted at this stage.

3.3. STAGE 2—INTRODUCTION OF LANDING TOLERANCES

For each point on this y_0' V_0' curve there will be an associated region enclosing points which become acceptable on the introduction of the landing tolerances y_1, V_1. This region is readily calculated as shown in Fig. 18, corresponding points on this diagram and on Fig. 11 being similarly annotated, and the introduction of the landing tolerances requires merely the application of Fig. 18 to every point on the y_0', V_0' curve and the plotting of the envelope of all the resulting limiting parts. This is readily achieved by pricking round a diagram of Fig. 18 drawn on a small piece of tracing paper; a process illustrated in Fig. 19.

3.4. STAGE 3—FINAL CORRECTION

The curve for the same limiting conditions, but with $T = 15$ seconds derived as above, passes outside the $T = 20$ seconds curve, indicating that for certain combinations of lateral displacement and lateral velocity the necessary corrections could be made in 15 seconds, but could not be made in 20 seconds. This state is obviously unrealistic and arises because, to allow a simple mathematical treatment, only one type of curve has been postulated for any set of starting conditions. To overcome this difficulty more flexibility must be introduced and alternative paths based on the mathematical treatment already described may be derived as follows.

Consider a combination of y_0 and V_0 which is possible from 15 seconds away, but implied by the mathematical treatment to be impossible from 20 seconds away. If the aircraft be made to follow the acceptable 15 seconds path from 20 seconds away, it would arrive at a point 5 seconds away with small displacement, small

T	=	SECS.
$\hat{\phi}$	=	RADS
$\frac{d\hat{\phi}}{dt}$	=	RAD/SEC.

LIMITATIONS DUE TO RATE OF ROLL

$R = g\frac{d\hat{\phi}}{dt}T^3 = 32{\cdot}2 \times \quad x =$

N	$y_0' = \frac{R}{N}$	$\frac{Z_1}{Y}$	Z_1	$V_0' = \frac{Z_1}{T}$	$\frac{Z_2}{Y}$	Z_2	$V_0' = \frac{Z_2}{T}$
15		-2·25			-1·75		
14		-2·23			-1·77		
13		-2·21			-1·84		
12		-2·16			-1·94		
11		-2·05			-2·05		

AT $Y = 0$ $Z = \pm\frac{\quad}{60} =$ _____ = $V_0' = \pm$

LIMITATIONS DUE TO BANK ANGLE

$B = g\hat{\phi}T^2 = 32{\cdot}2 \times \quad x \quad =$

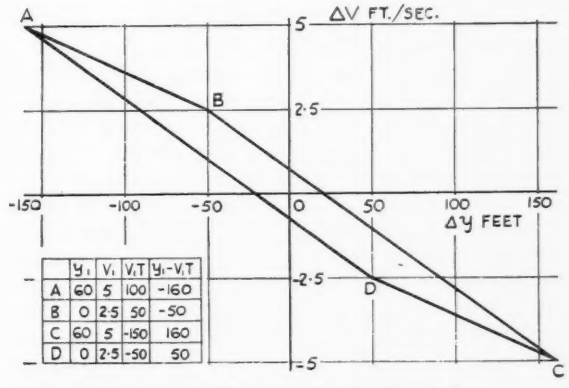
M	$y_0' = \frac{B}{M}$	$\frac{Z_1}{Y}$	Z_1	$V_0' = \frac{Z_1}{T}$	$\frac{Z_2}{Y}$	Z_2	$V_0' = \frac{Z_2}{T}$
3·7		-2·00			-2·00		
4·0		-2·33			-1·58		
4·2		-2·42			-1·39		
4·4		-2·49			-1·20		
4·6		-2·55			-1·01		
4·8		-2·61			-0·85		
5·0		-2·66			-0·69		
8·0		-3·39			-0·03		

AT $Y = 0$ $Z = \pm 0{\cdot}215B = \pm 0{\cdot}215 x \quad = \pm$

$V_0' = \pm$

FIGURE 17. Computing sheet for limiting loci.

tracking error, zero bank and zero rate of roll. It is apparent that the corrections necessary to bring it from this point to first acceptable touchdown within the runway criterion will, in practice, be small and as the aircraft has zero bank and zero rate of roll it is reasonable to assume that it could be kept level while maintaining its track. By following such a straight line path the aircraft would arrive at touchdown with zero bank, zero rate of roll and the same tracking error as it had 5 seconds away. The acceptable range of displacement at touchdown for any given tracking error is given by



	y_1	V_1	V_1T	$y_1 - V_1T$
A	60	5	100	-160
B	0	2·5	50	-50
C	60	5	-150	160
D	0	2·5	-50	50

RUNWAY CRITERION AS IN FIG. 11 $T = 20$ SECS.

FIGURE 18. Correction for runway tolerance.

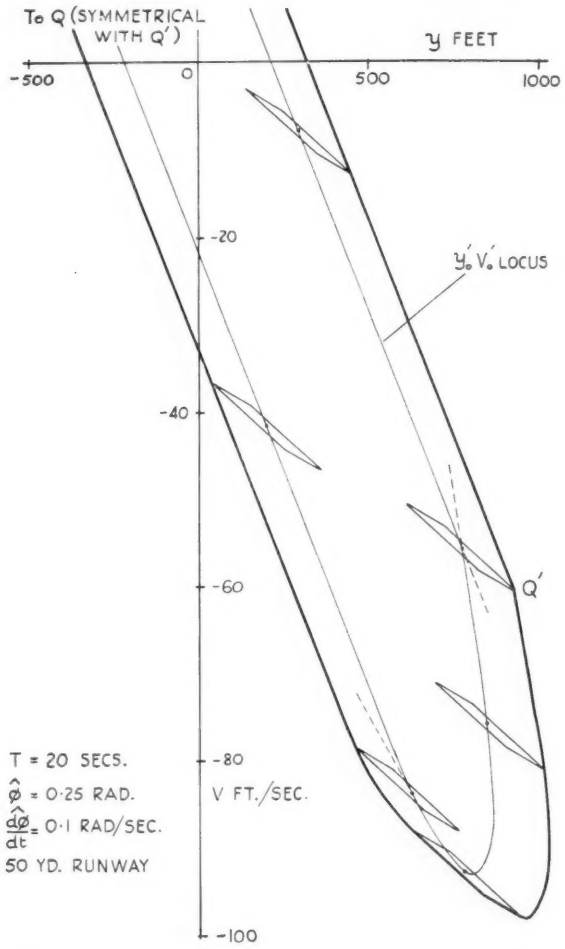


FIGURE 19. Construction of $y_0 V_0$ locus stages 1 and 2.

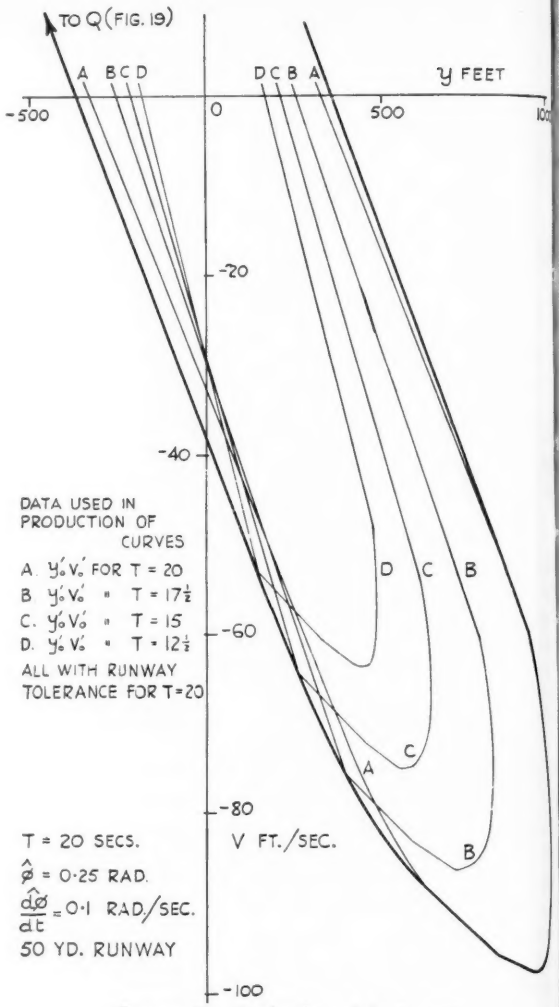


FIGURE 20. Production of final curve.

the runway criterion, from which can accordingly be calculated the acceptable combinations of displacement and tracking error 5 seconds earlier. Such a "portal" may be fitted into the calculations in exactly the same manner as the assumed runway criterion. The physical significance of this procedure is that an aircraft 20 seconds away is assumed to be made to follow either an acceptable sextic calculated for $T=20$ seconds, aiming to satisfy the runway conditions directly, or alternatively, to follow an acceptable sextic calculated for $T=15$ seconds, aiming to satisfy the 5 seconds conditions. In the second case the runway conditions will be automatically satisfied if the aircraft be kept straight and level for the last 5 seconds. It is apparent that this argument may be extended to give an infinite number of alternative tracks and the resultant flexibility in the analysis has been found to overcome the original difficulty.

The calculation of the portals and the associated tolerances is straightforward. If an aircraft is flying straight and level and arrives at first acceptable touchdown with displacement y_1 and tracking error V_1, its displacement τ secs. before would have been $y_1 - V_1\tau$ and its tracking error V_1, *i.e.* for the general point y_1, V_1 on the runway criterion chart, the corresponding point on the τ sec. portal will be $(y_1 - V_1\tau), V_1$. The corrections to be applied to the y_0' V_0' curve for time $T-\tau$ will thus be

$$\Delta y = (y_1 - V_1\tau - V_1(T-\tau) = y_1 - V_1 T$$

and $$\Delta V = V_1.$$

This is exactly the correction previously calculated from the runway criterion for application to the $T=20$ seconds curve.

The final 20 seconds curve is thus produced as in Fig. 20. Curves are produced by applying the 20 seconds runway tolerances to the y_0', V_0' curves for 20, 17½, 15 and 12½ seconds in turn. The final curve is the envelope of this series of curves, together with lines drawn tangential to the envelope through the unaltered points QQ' of Fig. 19. This latter course is taken to avoid a small re-entrant.

3.5. SUMMARY OF METHOD OF PRODUCING CHARTS

(*a*) Decide maximum allowable bank angle ($\hat{\phi}$) and maximum allowable rate of roll $d\hat{\phi}/dt$.

(*b*) For a given time T complete computing sheet shown in Fig. 17.

(*c*) Plot values of y_0' and V_0' so obtained.

(*d*) Repeat (*b*) and (*c*) for other values of T. (Intervals of $2\frac{1}{2}$ seconds are convenient.)

(*e*) Decide on runway criteria (*see* Fig. 11 as an example).

(*f*) Calculate associated correction for all values of T as in Fig. 18.

(*g*) To produce the final curve for a chosen value of $T=T_1$ apply, as in Fig. 19, the correction for $T=T_1$ calculated in (*f*) to the curves calculated in (*c*) and (*d*) for all values of T equal or less than T_1. The final curve is the envelope of all curves so obtained (*see* Fig. 20).

(*h*) Repeat for all required values of T.

Discussion

SIR WILLIAM FARREN: He thanked Mr. Mercer on behalf of the meeting for his excellent paper and had pleasure in calling on Mr. E. S. Calvert, whose work in this field was well known, to open the Discussion.

E. S. CALVERT (Royal Aircraft Establishment): Mr. Mercer had described clearly, concisely and precisely what automatic approach couplings would do. The Blind Landing Experimental Unit had a very high reputation, and he did not think that anyone was in a position to question their results. It was now up to the operators to look at those results and decide whether or not they wanted this equipment.

The performance of an approach coupling could only be stated in terms of approach success, as Mr. Mercer had done, but it was landing success which interested the operator. He would therefore like to make an attempt to show what these results implied in terms of landing success. Briefly, it appeared that if failures due to malfunctioning were excluded, a heading stabilised coupling gave an approach success of 100 per cent. at a distance of between 2,500 and 3,500 ft. from the glide path transmitter, depending on the amount of beam distortion. The limiting visibility for a *landing* success of 100 per cent. less the malfunction rate was, therefore, the visibility in which the visual guidance at distances of the order of 3,000 ft. was just good enough to enable the least skilful pilot to make the visual judgments which were necessary to enable him to execute manoeuvres such as those specified in Section 4 of the paper. The question then was what visual range would provide visual guidance at these distances with the patterns of visual aids which were, or could be, used.

Mr. Mercer had pointed out how necessary it was to stabilise the instrument portion of the approach by using a form of control which included a term related to the rate of closing the beam. Although this was well known, it was seldom realised that rate information was even more necessary to enable the pilot to stabilise the visual portion of the approach, and close the ground plane. He thought that the reason why few people realised this was that the mental processes involved in the visual appreciation of rates were largely subconscious. A study of how rate information was obtained from the visual field had recently been made, and if the further paper proposed by Mr. Mercer were ever written, it would probably include an account of this work; it was an extension of the parafoveal streamer theory of visual judgment.

Visual guidance did not suddenly vanish when the visual range fell below some particular value, but got progressively worse, the rate and rate rate indications disappearing before the displacement indications. This was simply a mathematical way of saying that the limiting visibility in which a pilot could judge the *tangent* to his track and appreciate how this tangent was *swinging* relative to the centre-line and aiming point, was higher than the visibility in which he could judge his position in space relative to the centre-line and aiming point. In other words, as the visual range fell, a point was reached at which the pilot, although seeing enough of the ground pattern to know quite well where he was, was unable to work out where he was going, *i.e.* his track heading. When this happened he could, of course, press on, and if he were skilful, and the coupling were good, the probability of making a successful landing would be high. However, as the visual guidance would be inadequate, the strain would be great, and the risk of accident might be increased beyond what was acceptable for this type of operation.

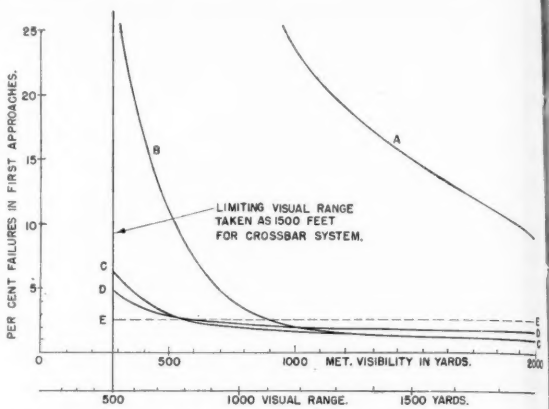
Mr. Mercer said that the transition from instrument to visual flight was probably the most important of all the problems involved in the approach and landing manoeuvre. He thought that the difficulties at transition were largely due to the difficulties of extracting rate information from the visual field when the visual ranges were short, and the observer was carried by a moving framework which had six degrees of freedom. Theoretical considerations and the results of operational research both seemed to indicate that even with the best patterns of visual aids, the rate and rate rate indications became inadequate for a safe transition at heights between 150 and 200 ft. when the visual range fell below about 1,500 ft. This, however, was an average figure applicable only to the types of aircraft which had been in operation during the past three years or so. The higher the approach speed, the more accurate the judgments of rate and rate rate which the pilot had to make, and the shorter the time available to make them. He had the impression that to land a large aircraft at an approach speed of 150 m.p.h. when the visual range was 1,500 ft., was close to what a human being could do with a level of safety acceptable in civil operations. If approach speeds increased, or if anything were done

to make the pilot's job more difficult, the limiting visual range would be substantially increased.

In a uniform fog a range of 1,500 ft. meant that the pilot of an aircraft with a downward view of 5 to 1 would make visual contact with a high intensity approach lighting system at a height of about 200 ft., which was about 4,000 ft. from the origin of a 3° glide slope. Taking this fact in conjunction with the results given in Tables I and II of the paper, it seemed that automatic approach couplings were already as precise as they needed to be, because they were already capable of bringing the aircraft down to heights of the order of 150 to 200 ft. with errors no larger than those which the great majority of pilots could correct visually at the limiting visual range which it was safe to use in regular operations. The operational value of automatic approach couplings could therefore be increased only by increasing their reliability, and making it easier for the pilot to monitor the approach and take over in case of failure.

A good deal of operational research had been done both in this country and the United States during the past three years to find out what levels of landing success were actually being achieved *in the field* with the various combinations of visual and non-visual aids now in use. This was fortunate, because the operator would naturally wish to compare the performance of the various systems before coming to a decision on which coupling to use for a particular type of operation. Some of these results were shown in the diagram (Fig. A), which showed the failure rate in first approaches plotted against the visibility. If it were assumed that all pilots could make manoeuvres such as those called for in Section 4 of the paper down to a visual range of 1,500 ft., then the performance curve for any particular automatic coupling would be a horizontal line drawn through the malfunction rate of the system, whatever that might be. According to his information, a reasonable figure for this might be 2½ per cent., as shown in the dotted curve *E*.

Several interesting conclusions could be drawn from the curves. In the first place, manual I.L.S. with only the cross-pointer meter gave such a low level of success as to indicate that something was fundamentally wrong with this coupling. He had little doubt that the poor performance was due to the fact that the only useful rate information in this system had to be obtained by the process known as "bracketing." When there was a varying cross-wind this was a slow, uncertain and difficult process and it seemed that at the approach speeds now in use, the pilot's job was already so difficult that, on the average, he failed to land in one out of every three first attempts as soon as the meteorological visibility fell to half a mile. What the pilot needed in order to make his job reasonably easy, and enable him to visualise where he was going, was a meter which presented rates as well as displacements. Alternatively, he might be given a second meter which told him what rates to apply, *i.e.* how to manipulate his track headings. Such instruments were now available, and were known as flight directors. The performance which might be expected for manual coupling using a



Curve A. Manual I.L.S. with cross pointer meter only
Curve B. Various approach lighting systems as used in U.S.A. G.C.A. approaches. Double row high intensity approach lighting system 1,200 ft. long
Curve C. G.C.A. at London (actual)
Curve D. Manual I.L.S. with Flight Director
Curve E. Automatic I.L.S.
} Centre-Line and cross bar system 3,000 ft. long

FIGURE A.

flight director in combination with the crossbar system of approach lighting was shown in curve *D*.

If these curves were representative, and he believed that they were, then it appeared that the three rate-using couplings, G.C.A., manual I.L.S. used with a combination of rate and displacement information, and automatic I.L.S., would all give a high level of landing success down to the visibility at which the visual aids began to fail. In other words, it made little difference to landing success whether the rate information were fed into a human pilot through his eyes or his ears, or whether it was fed into the automatic pilot through an automatic computer. When automatic approach couplings became operational, it might turn out that rate information had to be fed into the human pilot in any case in order to enable him to monitor the approach and take over quickly in case of failure. If this proved to be the case, then the arguments for automatic approach couplings would rest on grounds other than approach success. This was another reason for having a further paper on the subject with an authorship such as Mr. Mercer proposed.

It also appeared from these curves that an important factor in determining the number of overshoots per year, and to some extent the number of diversions, was the failure rate in meteorological visibilities above about 600 yds., because the great majority of instrument approaches would be made in this region. The fact that the failure rate in this region was nearly constant meant that down to a meteorological visibility of about 600 yds., visual guidance was adequate to enable practically all pilots to correct their errors, provided that the non-visual system was working properly. The failure rate in this region could therefore be regarded as a malfunction rate inherent in the non-visual systems as operated in the field. In view of the low malfunction rate of G.C.A., it seemed that there was much to be

said for this coupling where there was no language difficulty. To get the best out of G.C.A. it was necessary that the patter used by the talk-down controller should emphasise the rate information.

If, for the average pilot, visual guidance began to be inadequate for safe landing at some visual range which, for present types of aircraft, was of the order of 1,500 ft., then any coupling used in visual ranges below this must combine high reliability with high precision right down to touch. If one thought that this combination could not be achieved for many years to come, then one was driven to the conclusion that the only way of improving regularity in air transport during the foreseeable future was to use FIDO. When he himself was a passenger he put safety and regularity above speed, and the shorter the distance the truer that was. He would be interested to hear what some of the pilots present thought about this way of looking at the general problem of landing in fog.

MR. E. W. PIKE (British Overseas Airways, Control and Navigation Superintendent): Although he was with B.O.A.C. he was not a practising pilot, but had been concerned with a number of international discussions on this subject. At one of them Mr. Mercer had made a classic remark when saying that he thought the objective was not to produce new systems, but was basicly to land aeroplanes with safety and regularity in bad weather.

Mr. Calvert mentioned the critical height factor, with which they were all intimately concerned. It was now well known that a pilot on an instrument approach had to have a decision height, at which, if he was not satisfied with the approach, it had to be broken off. That, internationally, was known as the "critical height."

One of the difficulties was that, at present the pilot never really knew when he had reached that critical height. It was a recognised fact that the pressure altimeter to which he must refer had a possible error which was accepted as being of the order of ± 50ft. The pilot had no other means of making any other check on his height on the glide path except by reference to marker beacons, and this uncertainty about height directly affected operating limits.

Mr. Mercer had stated—he thought quite rightly—that the problem was to cope with existing I.L.S. Many opinions had been expressed by radio technicians at many conferences about difficulties with I.L.S. and that it was not really a highly satisfactory system. He would like to ask Mr. Mercer whether, in his opinion, if a system were produced having much better technical characteristics than I.L.S.—a much more stable beam—they could expect much greater approach success; and, if so, whether it would in any way alter his observations on the argument "rate *v.* heading"?

MR. H. C. PRITCHARD (*Fellow*): The quantitative information on beam distortion and the proof by flight experiment that rate stabilisation was not satisfactory in the presence of that distortion was very interesting indeed. In 1934, in a discussion following a lecture before the Society, Mr. (now Sir Robert) Watson-Watt said that one would generally expect a beam with a very fuzzy zero due to the effect of reflecting objects. They knew now how correct his prophecy was, but it was rather sad that known methods of producing a good beam had not been utilised when it was known 20 years ago that the beam would not be very good.

He thought it was true to deduce from the results given by Mr. Mercer that the heading stabilised system was also adversely affected by beam distortion, although not to such an extent as the rate stabilised system, which, he thought, would be the better system, from the general point of view, in the absence of beam distortion. He would like to ask Mr. Mercer whether rate stabilisation would be acceptable in the absence of beam distortion but that heading stabilisation was also affected, and whether a beam much less subject to distortion could be produced by, for example, using shorter wavelengths and other means?

The economic advantages of being able to operate without interference from terminal conditions were well brought out by Mr. Masefield in a paper a few years ago, particularly for high-speed civil aircraft. He had been in Australia for the past three or four years, and found that he could start off from home in the morning, do a full day's work 400 miles away, and be back in time for dinner. He could be sure of being back in time for dinner and, incidentally, the airlines there made a profit.

They seemed to be very slow in approaching this desirable state of affairs in Great Britain, and he doubted whether the efforts of the small team of radio and instrument men, who had done such a thorough job of work in their fields, really were sufficient to provide an early solution to this very difficult problem. As they made progress, the aircraft and power plant men made the job a bit more difficult, and he doubted whether they were catching up at any discernible rate.

Therefore he welcomed Mr. Mercer's remarks that he hoped to collaborate more and more closely with experts in the field of lighting, meteorology, etc., but he did not mention the power plant experts or bring in the aircraft designers. He believed that in the past two lectures before the Society, not one contribution in the discussion came from a power plant or aircraft designer; he hoped that this would not be the case on this occasion.

It was essential for the aircraft and power plant designers to become really usefully and vitally interested in the overall problem of defeating terminal conditions. If the problem were left solely to the radio and instrument experts, and if the tremendous potential for progress in all aviation matters which was available in the aircraft and power plant industries were not applied to the problem, he thought a great mistake would probably be made.

CAPT. BRESSEY (British European Airways): He would prefer to speak purely as a practising airline pilot, and not have anything attributed to him as being the view of British European Airways or anybody else.

He would agree that automatic approach—when it worked—did a very good job. He was sorry that Mr.

Mercer had not given any figures as to the serviceability rate of automatic approach gear. But as Mr. Mercer had pointed out the approach was only part of the job.

One could not step out at 200 ft. He often wished one could, as the most difficult part was the transition. The ease of transition from instrument to visual flight was the most important single factor in approach success. Also, he thought that this ease of transition depended on three things. Two of them were generally agreed, but the third was not.

No. 1, of course, was the accuracy of the instrument approach—that was quite obvious. No. 2 was the amount of concentration necessary during that instrument approach, in that if the pilot could make the instrument approach in a fairly relaxed condition, he would have much less difficulty in jerking his gaze from an instrument panel two ft. in front of his face to a row of approach lights some 2,000 ft. away.

No. 3 was the amount of mental strain involved during the instrument approach, which was slightly different from No. 2. No. 2 was concentration; No. 3, he would say, was what the French so charmingly described as "the pilot's tranquillity of spirit" and what certain irreverent co-pilots of his acquaintance referred to as "the Captain's twitch factor."

He was interested to see that this last factor—name it how they would—had now received official recognition from no less a body than the Ministry of Civil Aviation, in that someone responsible for G.C.A. patter at London had had it altered fairly recently. He would like to give an illustration of that alteration, to show what it meant to the pilot.

If one came into London to land on runway 28 left some time ago, in a very condensed form part of the patter would go something like this:—"Your heading two nine zero is good. You are on the glide path three miles from touch down. Your heading two nine zero is good. You are on the glide path two and a half miles from touch down. Your heading two nine zero is good. You are on the glide path two miles from touch down. Turn left left five degrees on to a heading of two eight five. You are on the glide path one and a half miles from touch down. Turn left left a further three degrees on to two eight two. You are on the glide path one miles from touch down." And by the time you were one mile from touch down, you were usually visual.

He submitted that this G.C.A. patter fulfilled all the requirements of his points 1 and 2. You had been given a perfectly accurate instrument approach. The amount of concentration necessary was fairly small. You just did what the G.C.A. man told you to do—that was quite easy. But any pilot knowing he was coming in to land on runway 28 at London, of which he thought the exact magnetic heading was 279, was a little worried at this continual "two nine zero is good." He had already had his weather given him, and unless he had a very strong cross-wind he would know that he had probably only two or three degrees of drift. He did not like the idea of coming in from three miles to one mile at ten degrees off the runway heading.

Somehow—he wished he knew how—(evidently G.C.A. controllers and pilots got together over a pot of beer one night), this fact came out. Somehow it worked its way through the hierarchy, and the G.C.A. patter of London had now been altered. If you had come in that afternoon, for example, on runway 28 under the same conditions, the patter would go something like this:—"Your heading two nine zero is good. You are on the glide path three miles from touch down. You are left of the centre line and closing. Your heading of two nine zero is good. You are on the glide path two and a half miles from touch down. Your heading of two nine zero is good. You are on the glide path two miles from touch down. You are coming up to the centre line now. Turn left left five degrees on to a heading of two eight five. You are on the glide path one and a half miles from touch down. You are going slightly right of centre line now. Turn left left a further three degrees on to two eight two. You are on the glide path one mile from touch down."

There was no difference in the actual information necessary for the pilot to fly his aeroplane in either of those two G.C.A. patters, but the level of their tranquillity of spirit was considerably raised by the fact that in the patter which they got now, they were being put in the picture all the time. They knew exactly, first of all, why they were carrying on on two nine zero. They were told when they were coming up to the centre line, and were even told that they had gone a bit to one side and must come round a further three degrees to bring them on. So although the path was exactly the same, the wear and tear on pilots' nerves these days was considerably less than a few months ago.

Mr. Calvert, who always put the pilot's view a lot better than any pilot could do himself, had said that the pilot should at all times be able to visualise that the path which the aircraft was following was the desired approach path. If this were done, the pilot was able to retain his frame of reference, and if they made him fly the aircraft manually he was forced to do so. That, he thought, underlined one of the major disadvantages of automatic approach.

On automatic approach, if his points 1 and 2 were satisfied, they had an accurate approach. The amount of concentration was not very great, although Mr. Mercer said that the pilot monitored the approach. Unless somebody invented a much better instrument than the cross-pointer indicator and fitted it, together with automatic approach, he did not think it could be said that the Captain was monitoring an approach from an I.L.S. cross-pointer meter. If they gave him some sort of flight director system (especially the Collins), he was in the picture all the time; but if they gave him that, he could probably make almost as good a job of the approach if he flew the aircraft manually.

The pilot was not having a very comfortable time on the approach, because no pilot really trusted an automatic approach near the ground. He was being forced, as it were, to change horses in midstream, at a very awkward point on the approach, low down, in awkward configuration, when he had got to do this transition

from the automatic approach to manual, go visual, and complete the landing.

Then, what happened when—he would not say "if"—the automatic approach gear did not work, or, as so often occurred, the I.L.S. was not serviceable? The pilot had to do something else. If the something else were G.C.A., and it was good G.C.A., that was all right; but if his automatic approach gear went unserviceable—say, halfway down the approach—the pilot then must complete the approach himself manually, using, presumably, the ordinary I.L.S. meter.

As Mr. Mercer said, that was not an easy job. With the present aircraft that were coming into service, it was getting more and more difficult. The only way that the pilot could cope at all was through constant practice. If they fitted automatic approach gear, how was the pilot to get that practice? He would need it some time. He did not think even Mr. Mercer would claim 100 per cent. serviceability for automatic approach gear.

There was another rather practical point. One of the several disadvantages of the profession of airline pilot was that he had to prove his practical ability as a pilot twice every year to get his instrument rating renewal, and as part of that he would have to do a manual I.L.S. on his aircraft, probably with one engine out. Check pilots being what they were, they usually chose the worst engine, and if the pilot had been sitting back on automatics for the past 80 or 90 days (or $5\frac{3}{4}$ months, if he had a six months' check), he certainly would not get through his check. Perhaps that was something for the pilots to worry about; but being out of practice on I.L.S. and then finding that the automatic approach did not work or went out of service half way down, was not a very happy state of affairs.

Mr. Pritchard asked whether they were catching up with all the technical developments of aircraft as regards performance and what the passenger really wanted—that was, reliability. They were not. He thought that they had gone downhill very badly. Sometime around 1935 Imperial Airways were flying a wonderful old machine called the Handley Page 42, and the common aeroplane in Europe was the Junkers Ju. 52. In those days they were not nearly so hemmed in with regulations as they were today and there were no such things as "mandatory limits," although most pilots stopped flying when the weather got really bad. There were one or two very brave men who used to carry on a bit longer, but not many of those were with them now.

Most people in those days used to stop when the cloud base got down to 300 ft. and the visibility got down to about half a mile. If one looked at the operators' limits now, for example, in America, for what they called "skedule passenger flying," one found that the vast majority of those operators stopped flying when the cloud base was 300 ft. and the visibility three-quarters of a mile—that was 18 years after 1935.

On this side of the Atlantic, operators' limits varied very largely. If they came into a place with all the aids for landing and long runways, such as London, then the limits were fairly low; but if they took a Gallup Poll of operators' limits for the majority of airfields in Europe, and especially airfields not provided with precision aids, it would be found that the limits were still around 300 ft. and upwards of half a mile.

There must be a reason for that. He did not think pilots had become all that dim in the past 18 years. The answer was that in 1935 the H.P.42 and the Junkers Ju.52 approached at between 60 and 70 miles an hour. They had wing loadings in the landing configuration of less than 20 lb. to the square foot, which meant that they could literally be thrown around just as the pilot liked; and coming down, not breaking cloud until 300 ft., the pilot had all the time in the world to think things out. He might have a line of flares on which to land, or he might not. But that was much easier than coming in on an aircraft at 150 miles an hour with a wing loading in the approach configuration, perhaps of 50 lb. to the square foot.

In those far-off days, a well-known editor of *The Aeroplane* was always calling for aircraft which landed slowly and which did not burn up. Using kerosine but not petrol, they were partly on the way to that last requirement. He was also extremely fond of quoting an American friend of his called Bill Stout, who was something in the aviation industry in America and who, when asked for a recipe for a good commercial aeroplane, just said "Simplicate and add more lightness." With respect to the chairman, the modern designer said "Complicate and add more heaviness."

In the latest aeroplane to come from the Douglas stable—the DC-7—they were very proud of hanging 25,000 lb. extra weight on to exactly the same wing as in the DC-6. In the landing configuration with a weight of 95,000 lb. it would have a wing loading of about 74 lb. to the sq. ft. Some unfortunate pilots would have to bring this aircraft in under fairly low limits—operators were always calling for lower limits.

Speaking to a DC-6 pilot the other day, he asked "what speed do you come in at in a DC-6?" The DC-6 pilot replied, "150 miles an hour on the approach." He quoted the figures for the DC-7 and asked at what speed the DC-6 pilot would bring it in. The reply was "I should think, at least 165 miles an hour, with a wing loading of 74 lb. to the sq. ft."

He was sure Mr. Mercer had seen the work which had been publicised by Mr. Jenks, of the C.A.A., in the United States, on what he called the "ballistic effects of an aircraft," in which he said that although the pilot—or the automatic pilot, for that matter—might initiate a small turn, because aircraft were getting heavier and wing loadings and approach speeds were going up, the aircraft would not immediately deviate from a given track. Some figures quoted by Mr. Jenks were for an approach speed of 135 miles an hour and a wing loading of 45 lb. per sq. ft., when the lag in deviating from track would be five seconds.

Mr. Mercer would then say "Let us have all automatic approaches and glue the aircraft to the centre line so that it will not deviate." He thought that they were going the wrong way about it. He would like to see approach speeds coming down instead of going the other way. In getting aircraft which were more and more difficult to get on to the ground, don't let them give the

pilot a jolly good approach system but leave it to him how to sort out the transition and get on to the ground.

Mr. Calvert's idea of the "approach precipice" was only too true. If they were presented with an aeroplane coming in fast at a very low altitude, it had still to be got on to the ground somehow. There was a divided opinion among pilots as to whether it was better to have flown an aircraft all the way down the approach yourself, and so have the feel of the aircraft (and have an idea of its trim), and then carry out the final landing; or whether the pilot should let the automatic approach or his co-pilot do the approach and then hand it over. He inclined to the view that if only the approach could be made easy enough, the pilot was better off handling the aircraft himself the whole way down.

Mr. Mercer finished by saying that he would undertake an investigation of the results of plain I.L.S. with no frills. He could tell him now that it would be pretty disappointing as soon as he got into a large fast aircraft, because the information provided by the ordinary cross-pointer I.L.S. was just not good enough. He thought they had been left holding a baby which had grown into something of a Frankenstein.

When I.L.S. was first developed before the 1939-45 War, aircraft had approach speeds of 90 miles an hour or so and low wing loadings, and one could cope fairly well with that. But I.L.S. had been with them a long time. Aircraft were not getting any easier to handle on the approach and speeds were going up. Not only was the pilot getting less time in which to sort things out, but he was being given a much less responsive vehicle.

G. W. STALLIBRASS (Ministry of Transport and Civil Aviation, *Associate*): *Contributed*: His comments did not, of course, purport to represent the views of the Ministry.

B.L.E.U.'s work on automatic approach, so ably described by Mr. Mercer, had evident value, but they should ask themselves what the ultimate objective really was and if it were the right one. By-products of the work included useful information on the performance of I.L.S. itself and on the relative merits of rate stabilisation and heading stabilisation applicable to instrumentation for manual I.L.S. approaches: they brought out some of the meteorological questions to be answered; and they could reveal the limiting approach characteristics of the aircraft employed. But the big question was, were automatic approaches really applicable to present types of aircraft and, since conquest of the approach problem was only a transition stage in the mastery of automatic landing, should they aim at ultimately landing such aircraft automatically? He would say the answers were "No."

Successful commercial use of automatic approach would require provision and maintenance of the equipment in aircraft wherever they were flying, which could lead on some routes to unrequited expenses in carriage and maintenance during most of the year. It would be utterly dependent not only on the provision of first-class approach facilities at each aerodrome but on their maintenance to an immaculate performance standard—often a difficult and always a very expensive matter. At how many aerodromes on world routes could operators count on the standard of facilities provided and maintained at London or Idlewild?

It was common knowledge that aircraft approach speeds were continuing to increase and that handling characteristics on approach were not improving proportionately, if at all. Pursuit of automatic approach systems for this kind of vehicle requiring ever more accurate I.L.S., ever more reliable auto-pilots and couplings, costly FIDO schemes, increased restrictions in areas around aerodromes and greater strain on pilots, amounted to accepting almost any difficulties in a solution rather than attacking the cause of the problem itself. This lay in present aircraft performance which often condemned a pilot to cross the boundary at 110 knots or more and to manoeuvre on approach, not always comfortably, at speeds considerably higher.

A notorious business consultant once said that if he were called on for advice by a factory where machines were installed upside down on the ceiling, he would be proud to produce a plan for the most effective use of machines in this position. Was that not the situation they were drifting into today where a great scientific effort, particularly in electronics, was being put into devising apparatus for persuading pilots to proceed past the point at which they could take over manually as a safe routine if the complicated automatic ground/air system failed? And how did they remain in practice for taking over an I.L.S. approach manually if they had been required to leave it all to the automatic system on most previous occasions? Captain Bressey's comments put this point very clearly.

A useful development of B.L.E.U.'s automatic approach work would be to find what it was in aircraft performance that caused an approach to fail. For example, a slower and highly manoeuvrable aircraft could land successfully from a position that would leave a less manoeuvrable aircraft no alternative but an overshoot. Such information might already be known from work such as Sperry's in the U.S.A., and the main need might be to collate and publicise it. For busy routes in poor visibility areas a design enabling an aircraft to approach and land in much lower weather conditions than previously, might produce more profit through increased regularity than a higher cruising speed achieved at the expense of sensible approach characteristics. For many years the pilot would have to see part of the approach and the runway in order to check the automatic system and to take over manually if it failed. In fog this would require the artificial creation of "visibility" by some such means as FIDO, a good part of which might well have to be paid for by the operator. A docile aircraft whose need could be met by a smaller FIDO installation might reduce FIDO charges by as much as £100 per fog landing, as compared with estimates for the more difficult types of aircraft still coming into service today. Furthermore, good approach characteristics built into the aircraft would be something that the pilot could count on wherever he was flying. He could not do this today so far as provision of such aids as FIDO and I.L.S. were concerned.

Unfortunately, no aircraft designers had spoken at the meeting. They might have tossed the ball back to the operators to specify the performance they wanted. Did the airlines know in fact how much it would be worth paying for higher regularity on their particular routes and the extent to which vastly improved approach and landing characteristics would economically justify accepting a lower performance in other respects? While projects on automatic approach (and landing) systems might continue to provide brilliant technical results, as in the work at B.L.E.U., technical success should not blind them to the fact that it might be denied profitable civil application as a whole until as much attention was paid to improving the characteristics of transport aircraft during approach and landing.

N. E. ROWE (Blackburn and General Aircraft Ltd., *Fellow*, Chairman of the meeting for the latter half of the Discussion): They had had a survey, both in the paper and in the discussion, of one of the fundamental problems in aviation, especially as it was used for commercial purposes. The whole subject of low visibility operations was of vital importance to the future progress of air transport the world over, but particularly in North-West Europe. The lack of ability to operate under all conditions robbed air transport in those regions of much of its potential power. A solution to the problems would turn air transport into real transport which could be relied on all the year round.

It would be an interesting exercise in economics to decide whether some loss of performance, which might be reflected by the very much heavier characteristics on the approach, would provide an aircraft which could be brought down much more readily in bad weather than at present, and whether, despite the losses in speed and so on, including the extra time taken, it could be used so much more reliably that it would attract to itself a much greater volume of air transport. That was something that would be examined.

Contributed: Much of their progress in aeronautics was quite naturally and properly devoted to obtaining better overall economics in terms of higher speeds and payloads, greater ranges, and so on, but unfortunately in the process the problem of landing became steadily more difficult. In fact, it might be true to say that the pilot, with the aids supplied to him, was continually stretched to the utmost of his capacity in the approach and alighting process when the meteorological conditions were nearing the permitted limits.

One of the vital factors was undoubtedly the time during which the pilot had to make a decision to alight or go round again, and as approach speeds steadily rose his difficulties on this score steadily mounted. In consequence, when the weather closed down, there were wholesale diversions, delays and general disorganisation. Was it not time that an overall survey of economics was made to determine the loss which the Air Transport Industry was suffering, despite the apparent improvement in economics, because it could not give the reliable service which would attract such a very great increase in travel by air if it could be provided? Seen in this context the effort put into simplifying the approach and alighting might be much more justified than effort to improve economics by means which were tending to make the problem of landing more difficult.

He suggested that the slogan they should adopt was " let the pilots see " and Mr. Calvert's plea for FIDO had his wholehearted support. He thought that until they recognised this they would not make progress, and that the overall economy and the increase in air transport which would result would far outweigh the relatively small expense of FIDO at all major airports.

I. F. B. WALTERS (Senior Operations Officer, Civil Aviation Branch, Air Department, New Zealand): *Contributed from the New Zealand Division of the Society*: The author and his colleagues were to be congratulated on the paper. Before reading it he had thought that the function of automatic approach equipment was solely to relieve the pilot of a heavy cockpit workload and so leave him free to monitor the approach and perhaps allow more leisurely sampling and transition to visual conditions. It now appeared that by rejecting rate for heading stabilisation a high degree of approach success could be obtained on far from perfect I.L.S. installations. This might encourage the fitting of the necessary automatic equipment in civil aircraft for the following reason. It was perhaps not wrong to say that approach lighting systems had reached the physical and economic limit in what was known colloquially as the " full Calvert." To ensure approach success for an acceptable runway visual range the radio aid should position the aircraft reasonably oriented and within visual range of the approach lighting system. If this principle were accepted the radio aid would function as a " feed " to the approach lights which, in turn, would " feed " on to the runway. The job of the radio aid then was to place the aircraft on to the lights. Assuming standard glide slopes this meant that under the worst conditions the lights were seen at about 3,500 ft. from the threshold or, say, about 4,000 ft. from the glide path transmitter. It would be seen from Table I (Filton) and Fig. 8 that whereas a manual approach would be abandoned before the lights were seen, the automatic approach ensured a high degree of success for getting within sight of the lighting system. Some firm indication would be necessary to the pilot that the coupling was secure, otherwise the erratic swinging of the I.L.S. localiser needle would initiate overshoot action.

The beam contours shown in Figs. 6 and 8 were an indication of the thorough manner in which this study had been tackled. They should be obtained on all site trials so that an accurate assessment of the operational " fitness for purpose " of intended installations might be made. As I.L.S. was now internationally standardised the radio engineer would frequently be asked to install localisers on existing strips affected by either man-made or natural reflecting surfaces and after making such adjustments as were within his power he should present the contour picture. After this the responsibility for deciding whether or not to install lay elsewhere. The obtaining of the necessary data seemed to call for new calibration techniques, the much overdue use of photography in this class of aerial work, and

indicated that there was a place for the helicopter in flying units so engaged.

Results of the quantitative tests of both the "zero reader" and manually conducted approaches were awaited with interest.

MR. MERCER'S REPLY

Although the paper dealt solely with the problem of instrument approach, the discussion had turned very properly on the part played by approach systems in the overall problem of defeating bad weather in the approach and landing phase of flight. MR. CALVERT had shown clearly, and other speakers had supported him, that the amount of bad weather defeated would depend largely on the degree to which the lighting information required could be provided and that, if an instrument approach system could be made to give 100 per cent. approach success at a height of 150 ft., its accuracy would not be the limiting factor in the overall system. This contention, which he supported, emphasised the importance of FIDO as a possible means of easing the problem facing the lighting engineer, and indicated that the choice between competing approach systems, several of which were possibly capable of giving the required approach success, would rest on factors other than accuracy.

The competing systems would appear to be I.L.S.—flown either automatically or with a flight director—and G.C.A. CAPTAIN BRESSEY had brought out very strongly the importance of the pilot being able to visualise the path of the aircraft and particularly its relationship to the desired path. He indicated how well a good G.C.A. did this but appeared to doubt the possibility of achieving a similar picture using I.L.S. During some experiments conducted by B.L.E.U. in very bad weather the pilot of an aircraft being flown automatically on I.L.S. was called upon to give a running commentary on each approach. The recordings of those commentaries sounded remarkably like Captain Bressey's G.C.A. "patter" and showed that the required picture could be obtained from I.L.S.; the naturalness of the voice indicated that the "tranquillity of spirit" was very high. It was not his task, however, to choose between competing systems and in particular he did not feel that I.L.S. approaches should necessarily be made automatically. The concensus of opinion in B.L.E.U. was that where an aircraft was fitted with an automatic pilot it should be used on the approach, but that an auto-pilot should not be specially fitted to make automatic approaches. It was true that all the quantitative results in the paper had been obtained using automatics, but this might be viewed in much of the work as experimental convenience. The techniques described were applicable to any approach system and any approach system claiming the required accuracy should be proven by the methods described.

He was unable to give the figures on the malfunction rate of automatics called for by CAPTAIN BRESSEY and moreover, their experience was not typical. The auto-pilots used by B.L.E.U. were maintained by the scientific staff but, against this, were continuously subjected to experimental modification. The recording work at various sites mentioned in the paper was never held up by unserviceability of the auto-pilot and B.L.E.U. pilots all had great faith in the equipment and had used it regularly at heights below 100 ft. in all weathers. An important feature of the auto-pilot on these tests was its reliance on magnetic amplifiers rather than valves.

MR. PIKE and MR. PRITCHARD had raised the question of new beams. MR. PRITCHARD was correct in saying that heading stabilisation was affected by distortion and that, if an undistorted beam were available, rate stabilisation would probably be used. The need for such a new beam, however, was difficult to assess. In his opinion, the distortion likely to be obtained using I.L.S., particularly with the new narrow beam aerial systems, was tolerable, in that 100 per cent. approach success at 150 ft. would be obtained if the information were used along the lines developed in the paper. There might well be other factors which would make a change desirable but these should be fully discussed elsewhere.

He agreed with MR. WALTERS that information on beam contours should be collected for all sites and welcomed his support for the photographic method of doing the work. He doubted, however, if the beam contour picture alone would, for a long time, prove sufficient for a decision to be taken on whether or not to install. A better course would be to test the overall installation as described in the paper by recording about 50 actual approaches and determining the approach success achieved. He considered that work necessary until a firm correlation between such results and the associated beam contours had been determined.

Many speakers had supported his plea for a detailed study of the overall problem by workers in the many specialist fields involved. The economic survey advocated by MR. ROWE would form a most desirable background for this study in that very clear objectives could be stated. It could well be that MR. STALLIBRASS's contention that the ultimate aim must be blind touchdown was true, but in any case the great importance of the flying characteristics of the aircraft of the future had been emphasised. Except for the possible addition of some form of throttle control to keep the required approach speed down to that advocated for good visibility approaches, the flying characteristics of an aircraft might well not affect the performance on automatic approach very markedly. The problems presented by higher landing speeds, poor manoeuvrability and poor downward view, became acute in the visual landing phase of the overall manoeuvre for, by increasing the time for which adequate visual information was required, they posed greater problems for the lighting engineer who, in the face of physical limitations, was thereby unable to defeat the same amount of weather. All those factors required study by a group of the appropriate specialists.

The Determination of Turbulent Skin Friction by Means of Pitot Tubes

by

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SUMMARY:—A simple method of determining local turbulent skin friction on a smooth surface has been developed which utilises a round pitot tube resting on the surface. Assuming the existence of a region near the surface in which conditions are functions only of the skin friction, the relevant physical constants of the fluid and a suitable length, a universal non-dimensional relation is obtained for the difference between the total pressure recorded by the tube and the static pressure at the wall, in terms of the skin friction. This relation, on this assumption, is independent of the pressure gradient. The truth and form of the relation were first established, to a considerable degree of accuracy, in a pipe using four geometrically similar round pitot tubes—the diameter being taken as representative length. These four pitot tubes were then used to determine the local skin friction coefficient at three stations on a wind tunnel wall, under varying conditions of pressure gradient. At each station, within the limits of experimental accuracy, the deduced skin friction coefficient was found to be the same for each pitot tube, thus confirming the basic assumption and leaving little doubt as to the correctness of the skin friction so found. Pitot traverses were then made in the pipe and in the boundary layer on the wind tunnel wall. The results were plotted in two non-dimensional forms on the basis already suggested and they fell close together in a region whose outer limit represented the breakdown of the basic assumption, but close to the wall the results spread out, due to the unknown displacement of the effective centre of a pitot tube near a wall. This again provides further evidence of the existence of a region of local dynamical similarity and of the correctness of the skin friction deduced from measurements with round pitot tubes on the wind tunnel wall. The extent of the region in which the local dynamical similarity may be expected to hold appears to vary from about 1/5 to 1/20 of the boundary-layer thickness for conditions remote from, and close to, separation respectively.

1. Introduction

Skin friction accounts for most of the profile drag of aircraft at subsonic speeds and for a large proportion of the drag of ships. Knowledge of skin friction on wings and bodies is largely of an indirect nature, being based on the skin friction of flat plates and the assumption that small pressure gradients have little effect on it (*see* Squire and Young[1]). When pressure gradients are large, and as separation is approached, this assumption must break down. The type of problem which can be dealt with on this basis must be approximately two-dimensional, but there are important problems relating to heavily swept wings, edge effects and flows in junctions and corners for which present knowledge of skin friction is of the vaguest character. Development of reliable methods of predicting the growth of turbulent boundary layers has certainly, in part, been retarded by lack of precise knowledge of skin friction and this is scarcely surprising when the very existence of the boundary layer is due to the presence of skin friction. Thus, there is a real need for simple experimental methods which will enable skin friction to be determined in both two-dimensional and three-dimensional flows.

Measurement of skin friction, so far, has not proved to be easy—except for long pipes and channels, when it can be deduced from the pressure drop. Successful attempts by direct measurement of the force on a small element of surface have been made for flat plates or approximations to them. Kemp[2] in towing tests on pontoons in a ship tank was able to obtain local values of skin friction at large Reynolds numbers and up to the present time, these, together with overall measurements of drag, have constituted the main sources of knowledge of skin friction at large Reynolds numbers. Recently Dhawan[3] has also carried out direct measurements of the force on a small element of surface of a flat plate at medium Reynolds numbers and over a range of Mach numbers. For laminar flow at low Mach numbers, the measured skin friction agreed well with Blasius' theory and when the flow was turbulent the measurements agreed with the semi-empirical formula developed by Kármán[4]. Unfortunately the method needs great care and is not suitable as a general method of determining skin friction on aircraft in flight or on ships at sea, and even in the laboratory its difficulties are formidable. Fage and Falkner[5] measured skin friction on an aerofoil by means of small half-pitots set in the surface, such that they lay entirely in the viscous sub-layer adjacent to the surface. These half-pitots were calibrated in a rectangular pipe under laminar flow conditions for which the skin friction could be calculated. Fairly satisfactory agreement was obtained with values of skin friction

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deduced by velocity measurements used in conjunction with the simple Kármán momentum equation and with the predicted frictional drag obtained by deducting the form drag from the total drag. The technique, however, is a difficult one and it has not been repeated. The use of the momentum equation in conjunction with velocity traverses is a possible method of determining skin friction, but it is tedious and not particularly accurate, since differentiation is involved, and it is unsuitable for use as separation is approached. Fairly recently Ludwieg[6] developed an indirect method of obtaining skin friction by measuring the heat transfer from a small heated element let into the surface. This method was found to be moderately satisfactory in spite of the fact that the heat transfer depends on the (skin friction)$^{\frac{1}{3}}$. It needs to be calibrated however, since heat is conducted to the surrounding parts of the surface. In spite of these shortcomings, Ludwieg's method has enabled new and valuable ideas to be developed. Ludwieg and Tillmann[7] were able to establish, within the limits of their experimental accuracy, that there is a region near the surface in which

$$\frac{u}{U_\tau} = f\left(\frac{yU_\tau}{\nu}\right) \quad . \quad . \quad . \quad (1)$$

only. In this relation, u is the velocity at a distance y from the surface and U_τ is the friction velocity defined by

$$U_\tau^2 = \frac{\tau_0}{\rho} \quad . \quad . \quad . \quad . \quad (2)$$

where τ_0 is the skin friction stress. This result is independent of pressure gradient and of upstream disturbances. The region involved is of the order of 1/10 of the boundary layer thickness and is therefore many times the thickness of the viscous sub-layer which it includes. A relation of the kind represented by equation (1) was predicted by "mixing-length" theory, but only in pipes and channels was it ever put to the test, as in other cases there was no means of obtaining U_τ with sufficient accuracy. Close to the wall, in the viscous sub-layer, equation (1) takes the form

$$\frac{u}{U_\tau} = \frac{U_\tau y}{\nu} \quad . \quad . \quad . \quad . \quad (3)$$

and this is really the basis of Fage and Falkner's[5] half-pitot tube method. Further out, equation (1) has been approximated by the relation

$$\frac{u}{U_\tau} = 5{\cdot}5 \log_{10} \frac{U_\tau y}{\nu} + 5{\cdot}8, \quad . \quad . \quad (4)$$

which fits results from pipes and channels and Ludwieg and Tillmann's observations[7]. This form was suggested by mixing-length theory. Ludwieg and Tillmann[7], as a consequence of equation (1), were able to establish a relation between the skin friction τ_0, the Reynolds number R_θ based on the momentum thickness θ and the form parameter H. This has opened up new methods of calculating the growth of turbulent boundary layers (*see* Spence[8], Maskell[9] and Zaat[10]). Spence, in particular, analysed velocity profiles given by Fage and Falkner[5] and by Schubauer and Klebanoff[11] and, assuming the correctness of equations (1) and (4), was able to deduce from them acceptable values of the skin friction. This suggests that an experimental velocity determination for this inner part of the boundary layer would yield the skin friction if relation (1) were exactly true and if its precise form could be determined. Kempf and Karhan[12], in a recent paper, were bold enough to apply relation (4) to velocity measurements in the boundary layer of a large cargo ship, to determine the skin friction and the deterioration of the surface condition of the hull over a given period of time. The objections to this method, at present, are that it is not known (*a*) if (1) is strictly true and (*b*) the extent of the region in which it is likely to be true; neither is its precise form known, since the velocity measurements in pipes and channels have been made almost wholly with pitot tubes for which the displacement of the effective centre near the wall is unknown.

The object of the present investigation was to seek a simple method of determining the skin friction which could, if required, be applied to the surfaces of vehicles in motion through air or water as well as in the laboratory. Some consideration was given to the idea of measuring local rates of mass transfer, but it was decided that there was little to be gained over the heat transfer method. Instead, attention was focused on the implications of equation (1), assuming this to be strictly true in a limited region near the wall. This, it seems, must imply a kind of local or restricted dynamical similarity in this region, for which τ_0, ρ, ν and some representative length are the only independent variables. Stephens and Haslam's[13] method of determining transition by tracking a pitot tube along the surface suggested that it should be possible to convert the readings of such a tube relative to the local static pressure into local skin friction. This line of thought, in conjunction with the idea of a kind of restricted dynamical similarity, is developed in detail in Section 3 to yield a relation of the form

$$\frac{(P - p_0)\, d^2}{\rho\nu^2} = F\left(\frac{\tau_0 d^2}{\rho\nu^2}\right), \quad . \quad . \quad (5)$$

where P is the total pressure recorded by the pitot tube on the surface, p_0 is the static pressure at the wall and d is the pitot diameter. Experiments are described to verify this for the flow in a pipe, using four similar pitots, and to determine the function F. These pitots were then used to determine the skin friction at three stations along the walls of a wind tunnel. Finally, pitot traverses were made to determine the velocity distributions both in the pipe and at these stations. These are compared on the basis suggested by equation (1).

Notation

- ρ density of fluid
- ν kinematic viscosity of fluid
- τ_0 local skin friction
- y distance normal to surface
- u mean velocity component parallel to surface at distance y
- $U_\tau = \sqrt{\tau_0/\rho}$ "friction velocity"
- d outside diameter of circular pitot tube
- h width or thickness of flat pitot tube

P total pressure recorded by pitot tube
p static pressure at any point in boundary layer
p_0 static pressure at wall at position occupied by mouth of pitot tube
D internal diameter of pipe test section
p_1 pressure at beginning of test section
p_2 pressure at end of test section
L length of test section of pipe = 6 ft.
U_m mean velocity across pipe
$R = U_m D/\nu$ Reynolds number for pipe
δ value of y at edge of boundary layer
θ momentum thickness of boundary layer
δ^* displacement thickness of boundary layer
$H = \delta^*/\theta$ form parameter for velocity profile
$\bar{\delta}$ displacement of effective centre of pitot tube
U_1 velocity at edge of boundary layer
U_0 reference velocity at centre of working section of wind tunnel
$c_f = \tau_0/\frac{1}{2}\rho U_1^2$ local coefficient of skin friction
ε roughness height

2. Similarity Basis of Present Investigation

Ludwieg and Tillman[7] have presented evidence which suggests that

$$\frac{u}{U_\tau} = f\left(\frac{U_\tau y}{\nu}\right) \quad . \quad . \quad . \quad (1)$$

is true in a limited region near the surface, independent of pressure gradient and upstream disturbances. If this is so, then it seems likely that conditions in this region are functions only of the physical properties of the fluid ρ and ν, τ_0 and a suitable length.

Consider then the total pressure P, as read by one of a set of geometrically similar circular pitot tubes resting on the surface*, measured relative to the static pressure p_0 at the wall. Then $(P - p_0)$ is the dependent variable depending only on the independent variables ρ, ν, τ_0 and d, where d is the pitot tube diameter (taken as representative length). Consequently we must have

$$\frac{(P - p_0)\, d^2}{\rho\nu^2} = F\left(\frac{\tau_0 d^2}{\rho\nu^2}\right). \quad . \quad . \quad (5)$$

The displacement of the effective centre and scale effects on the reading of the pitot tube are absorbed into this equation. Thus there is a simple method for determining τ_0, provided that equation (5) is true and the form of F can be established. This can be done in a circular pipe or channel where τ_0 is calculable from the pressure drop. For a circular pipe of internal diameter D

$$\tau_0 = (p_1 - p_2)\frac{D}{4L} \quad . \quad . \quad . \quad (6)$$

where $(p_1 - p_2)$ is the pressure drop over a length L. Two precautions are necessary, (*a*) the pitots must lie entirely in the region in which equations (1) and (5) hold and (*b*) the pitot diameter must be small compared with the pipe diameter. If the results of measurements made with a set of geometrically similar pitots over a range of $(p_1 - p_2)$, *i.e.* τ_0, are plotted in the form suggested by equation (5) and are found to lie on a well defined curve, then the existence of a local dynamical similarity is established and the curve represents the function F. These pitots may then be used at any station on a wall, with falling or rising pressure gradient, for which a knowledge of τ_0 is required and the reading $(P - p_0)$ to τ_0 may be converted by means of this curve which has been established from the pipe experiments. If each pitot yields the same value of τ_0 or

$$c_f = \frac{\tau_0}{\frac{1}{2}\rho U_1^2} \quad . \quad . \quad . \quad . \quad (7)$$

then (*a*) the existence of a region of local dynamical similarity has been established and (*b*) the correct skin friction has been determined.

As already mentioned, equation (1) forms the basis of a method for determining the skin friction, provided errors due to displacement of the effective centre of the pitot tube are small enough to be ignored. The form of equation (1) is not very convenient for this purpose as U_τ occurs on both sides of the equation. Instead, if ideas concerning a local dynamical similarity are true, we can write for the reading of a pitot-static combination

$$\frac{(P - p)\, y^2}{\rho\nu^2} = \phi\left(\frac{\tau_0 y^2}{\rho\nu^2}\right) \quad . \quad . \quad (8)$$

where p is the static pressure recorded at a height y, or, alternatively, it could be the wall static pressure p_0. Here again the form of ϕ can be established from pipe experiments and both (5) and (8) can be used together as a check in any determination of τ_0, but at present considerable care is necessary in applying (8) close to the wall owing to displacement effects. Strictly, (8) should be written

$$\left(\frac{P - p}{\rho\nu^2}\, y^2\right) = \phi\left(\frac{\tau_0 y^2}{\rho\nu^2}\,,\ \frac{y}{h}\right) \quad . \quad . \quad (9)$$

where h is the width of the pitot tube, and in this form it could be used to investigate the displacement of the effective centre $\bar{\delta}$ which can be written as

$$\frac{\bar{\delta}}{h} = \psi\left(\frac{\tau_0 y^2}{\rho\nu^2}\,,\ \frac{y}{h}\right) \quad . \quad . \quad . \quad (10)$$

or in other equivalent forms.

Equation (5) was framed with circular pitot tubes in mind but it is equally correct for pitot tubes of other shapes. However, practical considerations suggest the use of circular pitots in the first place, as they can be made geometrically similar with a degree of precision that could not be attained for flat or fish-tailed pitots. There is a limit to the smallest usable diameter, set by considerations of damping in reading the manometer.

3. Description of Apparatus

(*a*) *Pitot Tubes*

The geometrically similar circular pitot tubes were chosen to have, as nearly as possible, a ratio of internal to external diameter of 0·600. This was done for a number of reasons. In the first place, Young and Maas[14] have determined the displacement of the effective centre, for conditions which are equivalent to those obtaining in a boundary layer several pitot

*Or similarly situated relative to the wall at a constant y/d.

diameters from the wall, and for this ratio of internal to external diameter. Secondly, the larger sizes of hypodermic tubing in stock have approximately this ratio. Thirdly, this type of tube is very robust—any thinner wall would be liable to damage and difficult to machine. Also, preliminary experiments showed that it was important to maintain a closely constant ratio of internal to external diameter and to be careful about burrs. Table I gives the dimensions of the tubes used.

Figure 1(*b*) shows the arrangement of the tube. The brass stem is $\frac{1}{8}$ in. diameter and the mouth of the pitot is 2 in. from the stem. With the exception of No. 4 pitot, the front part of the tube was made of stainless steel. It was bent so that the first contact with the wall was at the mouth, and was soldered into the brass stem 1·0 in. from the mouth.

The method of manufacture of the mouth was as follows. A piece of tube of roughly the desired internal diameter was chosen and one end was machined square to the axis. The tube was then bored out by a suitable drill which was used as a mandrill on which it rotated, while the outer wall was ground to the correct diameter to preserve a ratio of internal to external diameter of 0·600 to within about $\pm\frac{1}{2}$ per cent. The face was then honed to remove any burrs and the tube mouth was inspected in a Hilger projector (magnification × 50). The internal and external diameters were measured to 1/10,000 in. If the desired ratio of 0·600 was not attained to a sufficient accuracy the grinding process was repeated until this was so—great care being taken to get rid of burrs.

The pitot traverses were carried out using a flattened or fish-tailed pitot made from hypodermic tubing. The dimensions of the mouth were: breadth = 0·059 in., width = 0·006 in., width of opening = 0·002 in.

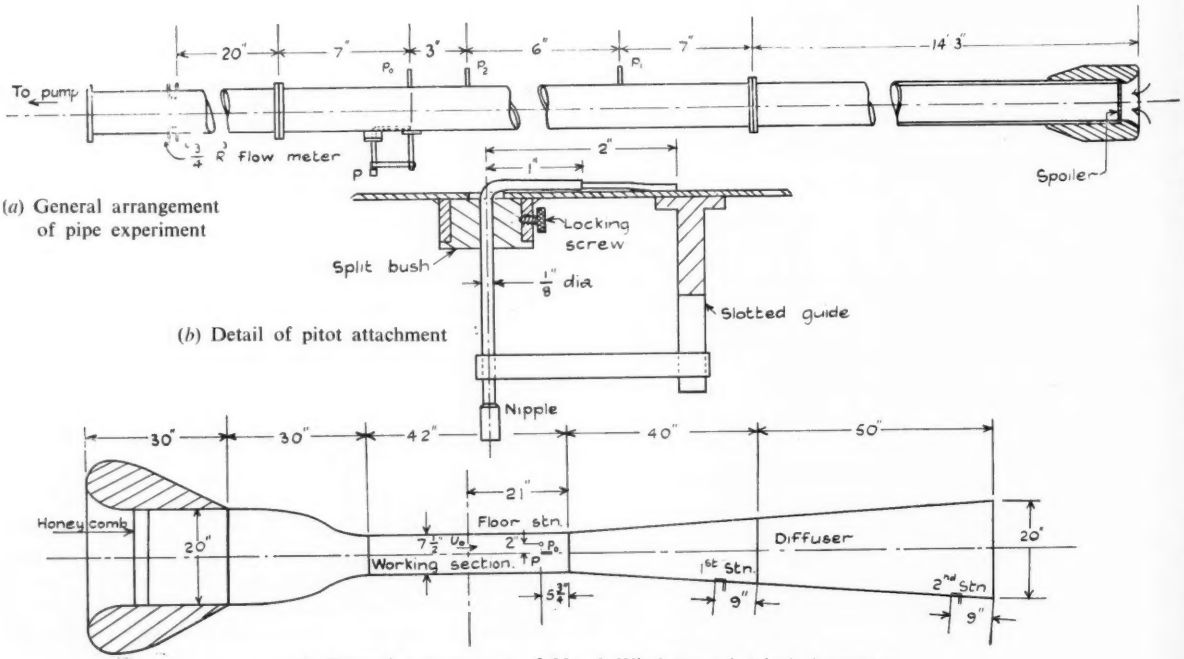
TABLE I

Pitot tube number	1	2	3	4
External dia. = *d* in.	0·02915	0·0544	0·0907	0·1214
Ratio: Internal dia./ External dia.	0·602	0·603	0·599	0·598

(*b*) *The Pipe*

The general arrangement, with dimensions, is shown in Fig. 1(*a*). The test section was preceeded by an entry length of 14 ft. 10 in. (89 diameters) of 2 in. internal diameter brass tube with a streamlined entry as shown. A slotted ring projecting 1/20 in. into the stream was located just inside the entry to act as a spoiler for promoting early transition to turbulent flow. The test section was chosen from a piece of carefully selected straight brass tube of 1/16 in. wall thickness with a very smooth polished internal wall. The average internal diameter was 1·996 in. This was determined by finding the volume of water required to fill the test section when the water and the pipe were at room temperature. Static pressure tappings were located at 7 in. and 10 in. from the downstream end to measure p_0 and p_2 and the tapping recording p_1 was 6 ft. upstream from the p_2 tapping. The holes in the wall were of diameter 0·02 in. and were finished smooth and free from burrs.

The pitot tube, resting on the wall, was held in a split bush located in a boss soldered to the pipe, so that its mouth was opposite the p_0 tapping. The pitot tube



(*a*) General arrangement of pipe experiment

(*b*) Detail of pitot attachment

(*c*) General arrangement of No. 3 Wind Tunnel (plan) Apparatus

FIGURE 1.

was pulled against the wall so that its mouth made contact and the locking screw in the boss was tightened. A bar soldered at right-angles to each pitot tube stem, and running in a slotted guide soldered to the pipe, maintained the pitot tube parallel to the pipe axis. A "three-quarter radius" pitot tube flow meter[15] was located 20 in. downstream of the end of the test pipe for recording the mean velocity of flow in the pipe. The end of the pipe was connected to a box fitted with four "vacuum-cleaner" type centrifugal pumps arranged in parallel. The speed of flow in the pipe was regulated by switching on the desired number of pumps and by a variable "bleed" in the wall of the box.

(*c*) *Wind Tunnel*

The wind tunnel working section and diffuser presented a convenient means for trying out the pitot tubes to determine skin friction, after their calibration in the pipe, as a range of boundary layer states associated with very slightly falling and rising pressure could be covered. Fig. 1(*c*) shows the general arrangement, with the pitot tubes located in the same manner as for the pipe experiments. The static datum p_0 was located 2 in. to one side of the pitot mouth. The working section had a well finished surface of hard lacquer and was aerodynamically smooth. The diffuser was of mahogany ply which was varnished and rough to the touch. This was sand-papered to remove the larger excresences, but it is possible that it was not aerodynamically smooth at the highest speeds.

4. Description of Experiments

(*a*) *Round Pitots on Wall of Pipe*

Two sensitive manometers of the null reading type, in which the movement of the alcohol meniscus in an inclined tube is observed, were connected so as to read $(p_1 - p_2)$ and $(P - p_0)$ respectively (*see* Fig. 1(a)). In this type of gauge, where the meniscus is observed against a sight under low optical magnification with a large field of view, it is possible, by suitably inclining the lines of sight, for one observer to observe both meniscii simultaneously. This enables a better accuracy to be achieved than can be obtained by two observers.

Preliminary experiments were made to ensure (*a*) that transition occurred at the pipe entry by increasing the spoiler height from 1/20 in. to 1/10 in. and (*b*) that the entry length of 89 diameters was sufficient to ensure uniform conditions along the test section by extending the entry length to 141 diameters. Readings of $(P - p_0)$ against $(p_1 - p_2)$ were then taken for all four pitots, the speed of flow in the pipe being varied from the lowest speed at which about one per cent. accuracy could be expected to the top speed. This corresponded to a range of Reynolds number $10^4 < R < 10^5$. Separate experiments were made to determine the effect of the presence of the pitot tube on the static pressure datum p_0. It was assumed that the pressure at the p_2 tapping—3 in. upstream of the p_0 tapping—was unaffected by the pitot tube, thus, by recording $(p_2 - p_0)$ over a range of $(p_1 - p_2)$ for each pitot tube and without the pitot tube, a small correction to p_0 was determined.

(*b*) *Round Pitots on Walls of Wind Tunnel*

Here much the same procedure was followed as before except that the variable chosen was the speed at the centre of the working section. This is given by calibration of the wind-tunnel manometer connected to the "hole in the wall" and atmosphere. This manometer was an ordinary U-tube using alcohol so that the simultaneous sighting of this gauge and the gauge reading $(P - p_0)$ was not possible, thus leading to some loss of accuracy. Also, due to an intermittent separation of the flow on one wall of the diffuser, the flow was not steady and observations tended to fluctuate about two positions for any selected value of U_0, which made the estimation of the mean difficult.

The velocity U_1, at the edge of the boundary layer at any station, was found by traversing a pitot-static combination.

(*c*) *Traverses by Flat Pitot—Determination of Velocity Profiles*

Two traverses were made at the p_0 station in the pipe at $R = 2{\cdot}55 \times 10^4$ and $R = 1{\cdot}03 \times 10^5$. Single traverses were made at the three stations in the wind tunnel at selected values of U_0. Tables II and III, Section 7, list the details. The static pressure variation $(p - p_0)$ through the boundary layer was also measured and proved to be small. From the values of $(P - p)$ the velocity u was found. The first and second diffuser stations gave considerable trouble owing to the fluctuations previously mentioned. For the latter station, a maximum fluctuation of about 50 per cent. of the mean was observed, which made it impossible to obtain an accurate mean.

5. Corrections and Accuracy, etc.

Static pressure corrections have already been mentioned in Section 4. The displacement of the effective centre of the flat pitot was taken from a rough estimate of Young and Maas[8] to be 0·25 of the width h. There is nothing very firm about this, but it was included as a correction at all distances from the wall in order to apply it at moderate distance $> 3h$, where a constant displacement may be expected to apply. At large distances its effect is negligible in any case. For distances $< 3h$ the effect of the wall becomes important and further research is needed to establish this.

The accuracy of the results for the round pitots on the wall of the pipe is believed to be high, as individual observations could be repeated to within about one per cent. The observations in the wind tunnel, particularly those for the second diffuser station, must be expected to show considerable scatter because of the unsteadiness already mentioned. The choice of this wind tunnel for illustrating the practical determination of skin friction was governed by the facilities available at the time and, although not ideal for the purpose, it nevertheless showed what could be achieved in the worst circumstances.

It may be noted here that, taking the mean velocity U_m from the calibrated three-quarter radius flow meter reading and U_τ from the pressure drop in the pipe and plotting U_m/U_τ against $\log_{10} U_\tau D/\nu$, very good

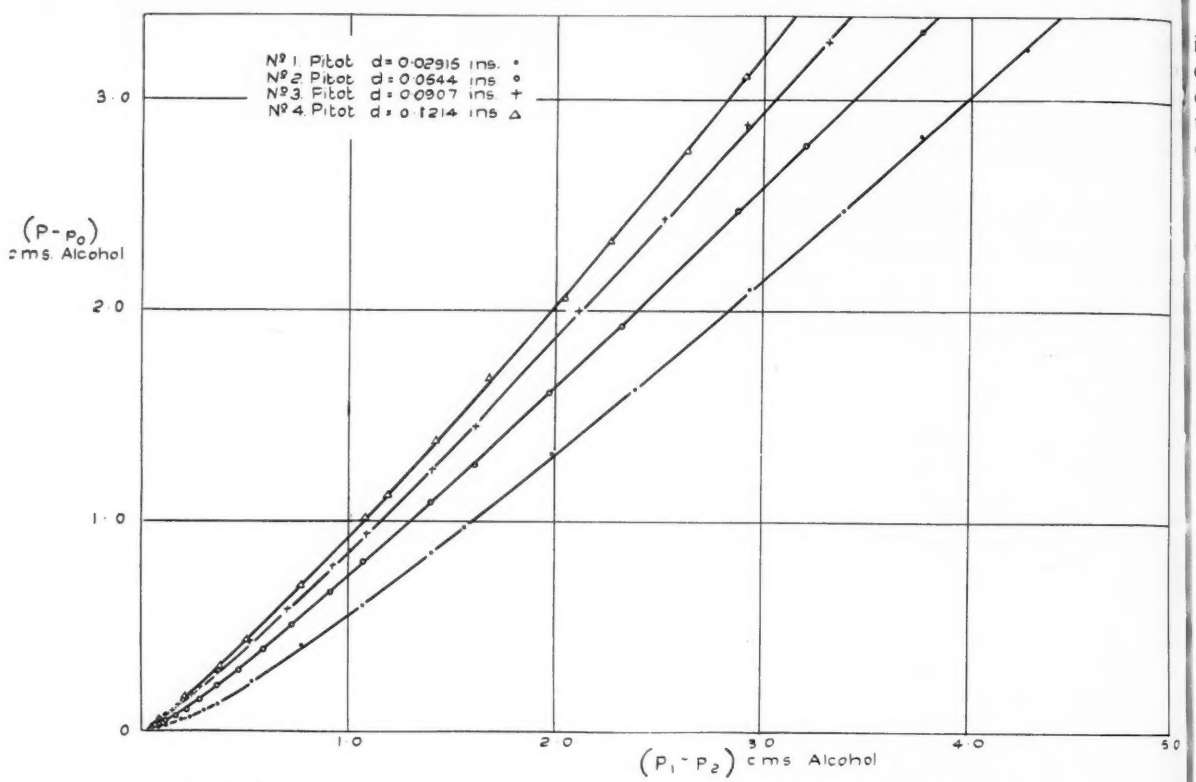


FIGURE 2. Actual observation for round pitots on wall of circular pipe, $(P-p_0)$ against (p_1-p_2).

agreement was obtained with the accepted relation*

$$\frac{U_m}{U_\tau} = 0{\cdot}29 + 5{\cdot}66 \log_{10} \frac{U_\tau D}{\nu} \quad . \quad . \quad (11)$$

over the present range of Reynolds number $10^4 < R < 10^5$. This further substantiates the adequacy of the entry length of 89 diameters when an entry spoiler is used.

The physical constants ρ and ν for air were those appropriate to the temperature and pressure obtained for each particular test, as was the density of the alcohol in the manometer.

6. Presentation of Results

Apart from Fig. 2, which shows the actual observations for round pitots in the wall of the pipe, and Fig. 4 which shows c_f against U_0, the remaining figures show the results plotted on the non-dimensional basis suggested by Section 2. Equation (5) was replaced by

$$\frac{(P-p_0)\,d^2}{4\rho\nu^2} = F\left(\frac{\tau_0 d^2}{4\rho\nu^2}\right). \quad . \quad . \quad (5a)$$

to facilitate comparison with the pitot-traverse results. Because of the wide range of variables covered, logarithmic plotting is necessary to show the results in a compact form. This compression of scales also compresses the scatter, and such plotting can be misleading.

*See *Modern Developments in Fluid Dynamics*, Vol. II, p. 338 (Oxford University Press).

Hence, to show the accuracy of the observations and any differences between results from different pitots or from different traverses, a non-dimensional plotting extending over several graphs of successively increasing scales was made. This plotting is not shown in the present paper owing to the limitations of space.

7. Results and Discussion

(a) *Round Pitot on Wall of Pipe*

Figure 2 shows the actual observations for the four circular pitots. The curves are well separated and the small scatter of the experimental points is noteworthy.

Figure 3(*a*) shows these results expressed in non-dimensional form and plotted logarithmically as $\log_{10} \tau_0 d^2/4\rho\nu^2$ against $\log_{10} (P-p_0)\,d^2/4\rho\nu^2$. The results for all four pitots now fall accurately on one curve, which for values of $\log_{10} (P-p_0)\,d^2/4\rho\nu^2 > 5{\cdot}0$ appear to be a straight line of slope 7/8, the equation to which is

$$\log_{10} \frac{\tau_0 d^2}{4\rho\nu^2} = \bar{2}{\cdot}604 + 7/8 \log_{10} \frac{(P-p_0)\,d^2}{4\rho\nu^2} \quad . \quad (12)$$

Also shown in Fig. 3(*a*) is the result for viscous flow assuming *no* displacement of the effective centre. This is the line

$$\log_{10} \frac{\tau_0 d^2}{4\rho\nu^2} = \tfrac{1}{2}\left[\log_{10} 2 + \log_{10} \frac{(P-p_0)\,d^2}{4\rho\nu^2}\right]. \quad (13)$$

The experimental curve tends to run parallel to this line at the lowest values of the variables.

From Fig. 3(*a*) excellent confirmation is seen of the ideas developed in Section 2 from the concept of a local dynamical similarity in a region near the wall, involving only τ_0, ρ, ν and a representative length. Furthermore, the well defined curve represents the function F in equation (5*a*), *e.g.*

$$\frac{(P-p_0)\,d^2}{4\rho\nu^2} = F\left(\frac{\tau_0 d^2}{4\rho\nu^2}\right). \qquad (5a)$$

This curve can now be used to convert readings of $(P-p_0)$ into values of τ_0 on other walls under falling or rising pressure gradients and whether rough or smooth, provided that the roughness height is small compared with the least pitot diameter.

(*b*) *Round Pitots on Walls of Wind Tunnel—Determination of Local Skin Friction*

The readings of the four round pitots on the surface at the three stations in the wind tunnel have been converted, using the experimentally established relation (5*a*), into values of τ_0 and thence into values of c_f—the local coefficient of skin friction defined by

$$c_f = \frac{\tau_0}{\frac{1}{2}\rho U_1^2}. \qquad (7)$$

In Fig. 4 c_f is shown plotted against U_0, the speed in the working section, for each of the three stations. There is some scatter which is due partly to unsteadiness and partly to the fact that c_f is the ratio of two experimentally determined quantities, which accentuates the scatter at the lowest speeds. Otherwise the points from the various pitots are evenly distributed about fairly well defined curves. The value of c_f at each station is found to be independent of pitot diameter, thus confirming the existence of a region of local dynamical similarity for (*a*) slightly favourable pressure gradient (station 1), (*b*) adverse or rising pressure gradient (stations 2 and 3) in the diffuser. The boundary layer at the last station in the diffuser is approaching separation. Furthermore, the values of c_f so deduced must be correct.

A more detailed examination of the curves of Fig. 4 reveals that, at the first station in the working section where the walls are smoothly finished, c_f falls at a decreasing rate as U_0 is increased. At the second station, where the diffuser wall is slightly rough, but where τ_0 is less than at the first station for given U_0, c_f first falls as U_0 increases and then tends to remain constant, thus showing that at the higher speeds the wall is becoming aerodynamically rough. At the third station the roughness is much the same, but, for given U_0, τ_0 is further reduced and so c_f continues to fall for higher values of U_0 than at the second station. Thus there is evidence suggesting that, even when the wall is *slightly* rough, the skin friction can be deduced from readings of round pitots on the surface.

(*c*) *Pitot Traverses and Velocity Distributions*

Figure 5 shows the velocity profiles in the usual form where u/U_1 is plotted against y/δ. Tables II and III give the important details.

The pipe velocity profiles and the profile for the working-section station lie close together, whereas the diffuser profiles lie successively lower. The observations

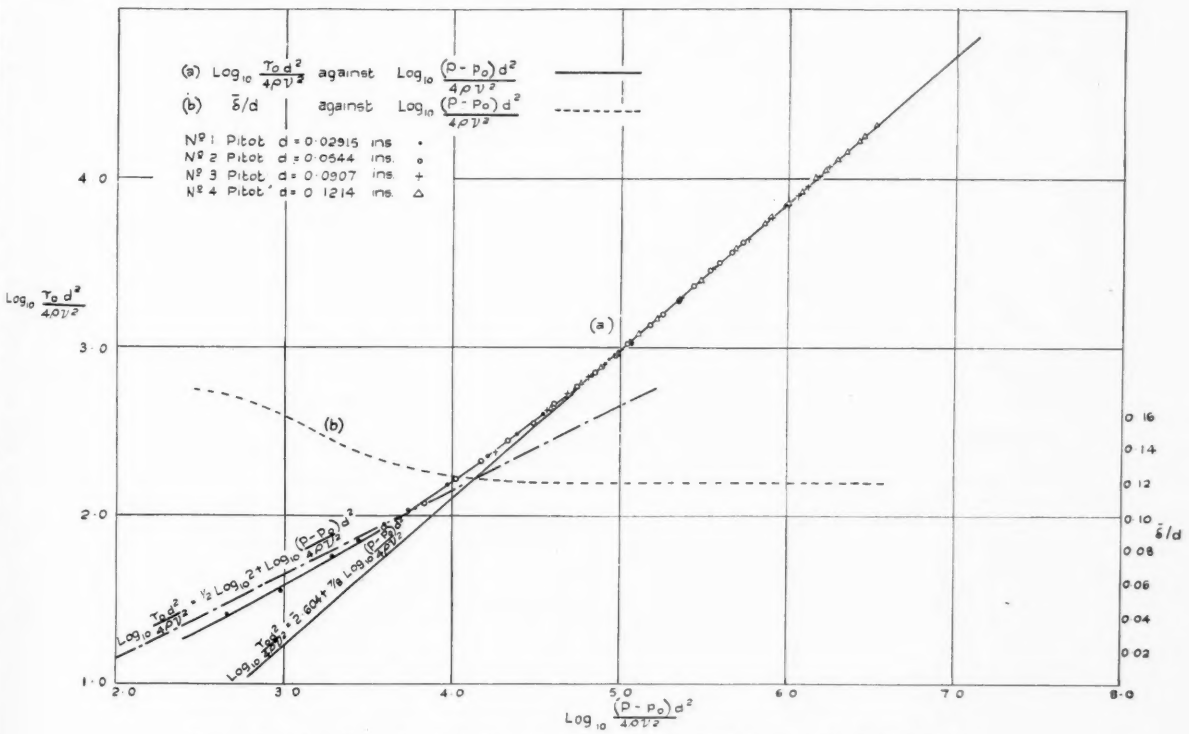


FIGURE 3. Non-dimensional plotting of results for round pitots on wall of circular pipe.

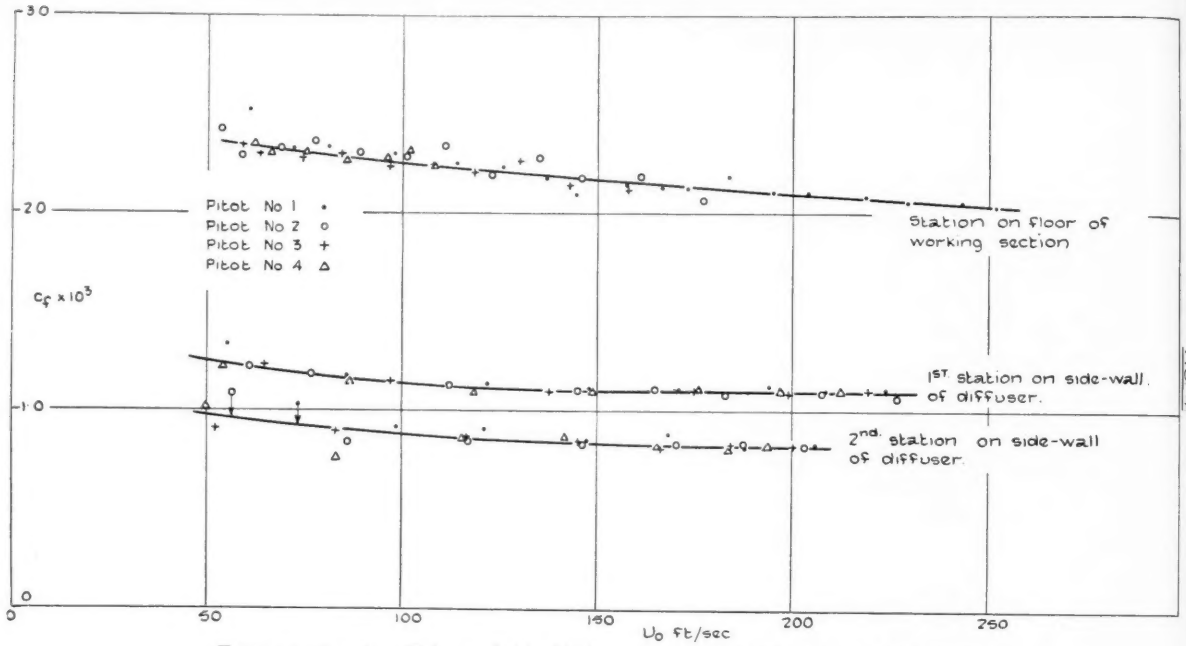


FIGURE 4. Local coefficients of skin friction at various stations in No. 3 Wind Tunnel as determined by round pitots on the surface.
$c_f \equiv \tau_0 / \frac{1}{2}\rho U_1^2$ against U_0 (speed at working section).

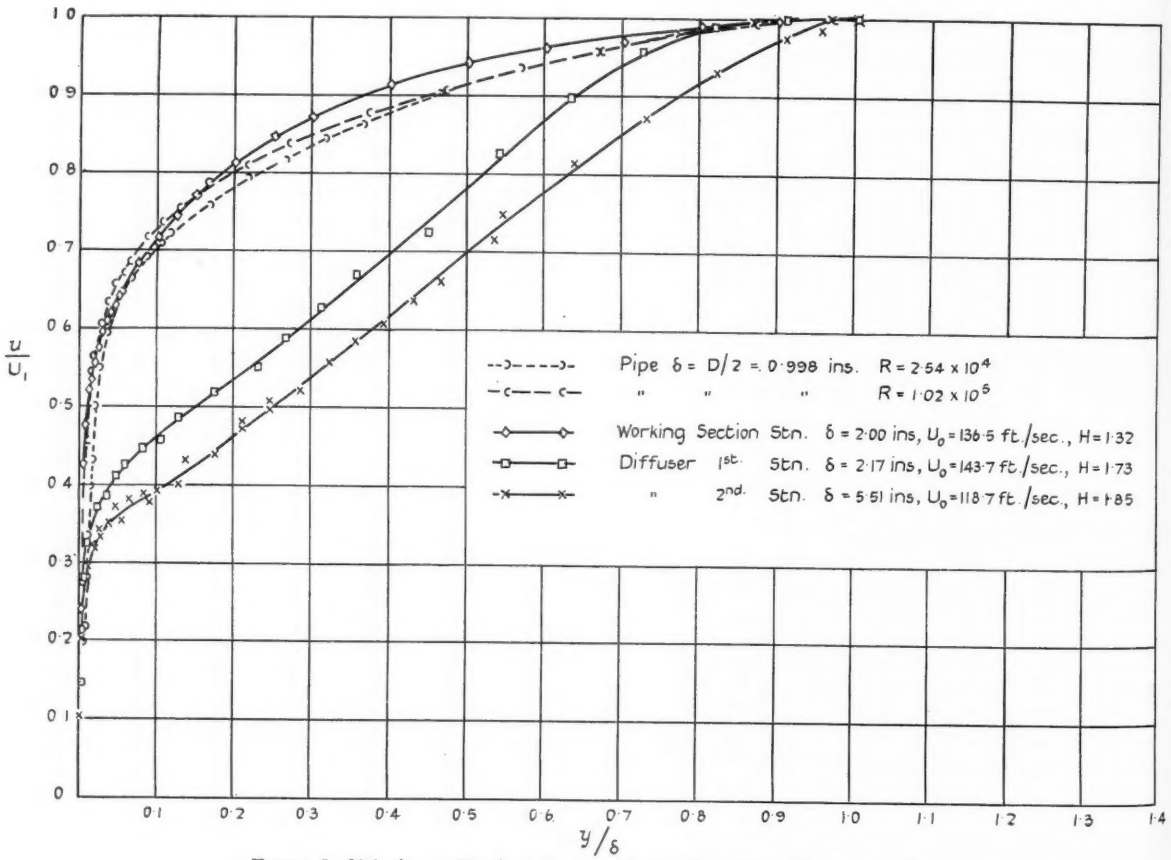


FIGURE 5. Velocity profiles from traverses by fine flat pitot, u/U_1 against y/δ.

for the second diffuser station (near separation) show considerable scatter.

Before discussing the remaining figures it may be noted that, for the pipe results, τ_0 was obtained from the pressure drop, and for the wind tunnel result, it was taken from Fig. 4 which gives the results of the round pitot measurements at the surface.

Figure 6 shows the plotting suggested by equation (8), Section 2. By plotting on a logarithmic basis the results can be compressed into a single figure at the expense of accuracy. $\log_{10} \tau_0 y^2/\rho\nu^2$ is shown plotted against $\log_{10} (P-p)\, y^2/\rho\nu^2$, where $(P-p)$ is the dynamic pressure at a distance y from the surface, with a rough correction for the displacement of the effective centre of 0·25 h. The results for the second diffuser station have been omitted, since the accuracy is so poor as to obscure the results from the other four traverses. Certain features are immediately apparent. The results from the different traverses spread at low values of $\log_{10} (P-p)\, y^2/\rho\nu^2$, which is almost certainly due to the pronounced displacement of the effective centre. Then there is a range of $\log_{10} (P-p)\, y^2/\rho\nu^2$ where the results fall together with slight scatter on a curve, which, at larger values of $\log_{10} (P-p)\, y^2/\rho\nu^2$, is well fitted by a straight line of slope 7/8. Finally, at large values of $\log_{10} (P-p)\, y^2/\rho\nu^2$, the results again diverge. Examination of the tables from which the results were plotted reveals that, at the low values of $\log_{10} (P-p)\, y^2/\rho\nu^2$, the results for the various traverses diverge from one another at $y/h \doteqdot 2{\cdot}5$, the curves for the larger $U_\tau h/\nu$ diverging first. This is consistent with the suggestion that the effect is due to the influence of the wall on the displacement of the effective centre. Thus the results at the lowest $U_\tau y/\nu$, *i.e.* the pipe results at $R = 2{\cdot}54 \times 10^4$, should be close to the result to be expected for an infinitely small pitot as far as $y/h \doteqdot 2{\cdot}5$. This is confirmed by the steady and close approach of the curve to the line representing the theoretical result for viscous flow. If the displacement of the effective centre for this pitot near the wall were known we might expect to collapse all the results on to a single curve as is the case at larger values of $\log_{10} (P-p)\, y^2/\rho\nu^2$, where, since y is fairly large, errors in estimating the displacement effect are negligible. The grouping together of all the results in this region provides further confirmation of the existence of our postulated dynamical similarity, and of the correctness of τ_0 as deduced from the round pitot experiments in the case of the two traverses in the wind tunnel. The final divergence at large values of $\log_{10} (P-p)\, y^2/\rho\nu^2$ is due to the fact that these points lie outside the region of dynamical similarity which appears to extend to $2y/D \doteqdot 0{\cdot}2$ for the pipe. Also shown on Fig. 6 is the curve for the circular pitots on the pipe wall taken from Fig. 3 by putting $y = d/2$. This curve lies below the results from the pitot traverses, showing that the displacement of the effective centre is outwards from the geometric centre, whereas near the wall the flat pitot appears to have its effective centre displaced inwards.

For large values of $(P-p)\, y^2/\rho\nu^2$ the results in Fig. 6 are well represented by the line

$$\log_{10} \frac{\tau_0 y^2}{\rho\nu} = \bar{2}{\cdot}628 + 7/8 \log_{10} \frac{(P-p)\, y^2}{\rho\nu^2} \quad . \quad (14)$$

The constant was selected to make the line pass through the pipe results in the range $y/h > 2{\cdot}5$, $2y/D < 0{\cdot}2$, $(P-p)\, y^2/\rho\nu^2 > 1{\cdot}5 \times 10^5$, as these results would appear to suffer least from displacement effects at the lower values of $(P-p)\, y^2/\rho\nu^2$ and they are *provisionally* taken as representing the results to be expected for an infinitely small pitot. Reasons will be given later for selecting the index of 7/8 in equation (14).

Figure 7 shows the results for the traverses plotted in the form of u/U_τ against $\log_{10} yU_\tau/\nu$ and compared with the accepted relation

$$\frac{u}{U_\tau} = 5{\cdot}5 \log_{10} \frac{U_\tau y}{\nu} + 5{\cdot}8 \quad . \quad . \quad (4)$$

suggested by "mixing length" theory, with the constants taken from pipe flow measurements near the wall. Also shown is the relation for purely viscous flow near the wall

$$\frac{u}{U_\tau} = \frac{U_\tau y}{\nu} \quad . \quad . \quad . \quad (3)$$

and the curve representing the results for the circular pitots on the wall of the pipe, putting $y = d/2$. On this plotting, due to the slight scatter of the various traverses, the accepted relation given by equation (4) above gives

TABLE II

TRAVERSES IN PIPE

Symbol	U_m *ft/sec*	U_1/U_m	U_τ/U_m	R	$\delta = d/2$ in.	$U_\tau h/\nu$	*Remarks*
⊃	24·0	1·245	0·0554	$2{\cdot}54 \times 10^4$	0·998	4·22	τ_0 from pressure drop
⊂	97·2	1·212	0·0470	$1{\cdot}02 \times 10^5$	0·998	14·4	τ_0 from pressure drop

TABLE III

TRAVERSES IN WIND TUNNEL

Station	*Symbol*	U_0 *ft/sec*	U_1/U_0	δ in.	θ/δ	H	$U_\tau h/\nu$	*Remarks*
Working section	◇	136·5	1·012	2·00	0·105	1·32	14·6	Slight pressure drop
1st diffuser	□	143·7	0·730	2·17	0·142	1·73	7·87	Pressure rise
2nd diffuser	×	118·7	0·582	5·51	0·169	1·85	4·67	Pressure rise

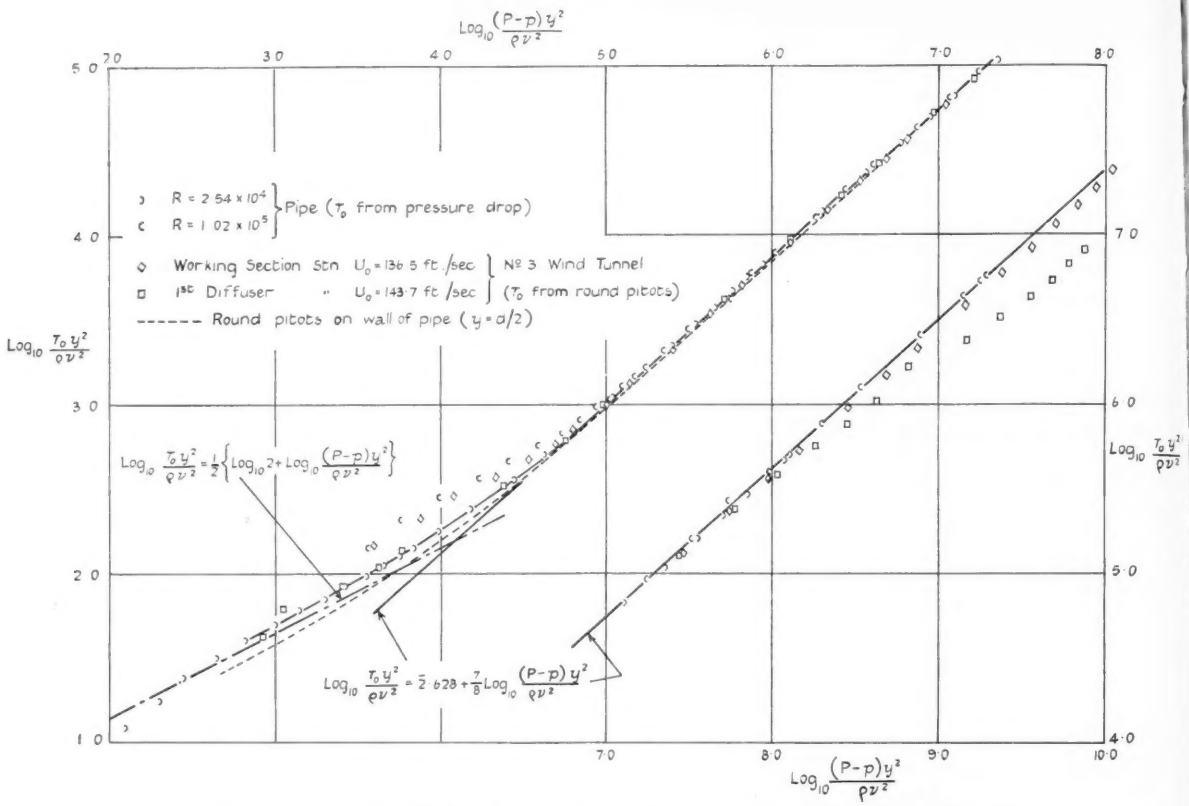

Log10 (P-p)y²/ρν²
R = 2·54 × 10⁴
R = 1·02 × 10⁵
Pipe (τ0 from pressure drop)
Working Section Stn U0 = 136·5 ft./sec
1st Diffuser " U0 = 143·7 ft./sec
Nº 3 Wind Tunnel
(τ0 from round pitots)
Round pitots on wall of pipe (y = a/2)
Log10 τ0y²/ρν² = ½{Log10 2 + Log10 (P-p)y²/ρν²}
Log10 τ0y²/ρν² = 2·628 + 7/8 Log10 (P-p)y²/ρν²
Log10 τ0y²/ρν²
Log10 y/U0
Log10 (P-p)y²/ρν²

FIGURE 6. Non-dimensional plotting of observations from various pitot traverses (flat pitot). $\text{Log}_{10}\,\tau_0 y^2/\rho\nu^2$ against $\text{Log}_{10}\,(P-p)y^2/\rho\nu^2$.

a quite acceptable fit. Now the "7/8-power" law suggested by Fig. 6 implies a "1/7-power" law for the velocity, but owing to the limited range of $U_\tau y/\nu$ for which dynamical similarity holds for these results, it is not easy to decide whether a "power" law or a "log" law gives the best fit, especially as in each case there are two constants at our disposal. This particular plotting brings out well the divergence of the various results at low values of $U_\tau y/\nu$ due to the displacement effect near the wall, which is greatest for large $U_\tau h/\nu$. The curve for the pipe at $R = 2{\cdot}54 \times 10^4$ has the lowest $U_\tau h/\nu$ and as already mentioned, this closely approaches the viscous flow relation, equation (3), before the displacement effect is seriously apparent at $y/h < 2{\cdot}5$. Fig. 8 shows $\log_{10} u/U_\tau$ plotted against $\log_{10} U_\tau y/\nu$. The relation, corresponding to equation (14) as deduced from Fig. 6

$$\log_{10}\frac{u}{U_\tau} = 0{\cdot}935 + 1/7\log_{10}\frac{U_\tau y}{\nu} \quad . \quad (15)$$

is shown in this figure. The slope of 1/7 represents the experimental points as well as the "log" law in Fig. 7. The question as to whether a "log" law or "power" law best represents

$$u/U_\tau = f\left(\frac{U_\tau y}{\nu}\right) \quad . \quad . \quad . \quad (1)$$

at sufficiently large values of $U_\tau y/\nu$ is difficult to decide by inspection of Figs. 7 and 8, because of the scatter of the points and the restricted range of $U_\tau y/\nu$ covered in the present experiments, but considerations on the displacement of the effective centre for the circular pitots on the wall will be shown to favour the "power" law.

(*d*) *Displacement of the Effective Centre of a Pitot Tube near a Wall*

It is now possible to deduce from the results so far obtained a *provisional* curve for the displacement of the effective centre of a circular pitot in contact with a wall. The displacement $\bar{\delta}$ may be expressed in terms of two non-dimensional parameters as long as the pitot lies in the region of local dynamical similarity. A form convenient for the present purpose is to write

$$\frac{\bar{\delta}}{d} = g\left\{\frac{(P-p_0)\,d^2}{4\rho\nu^2},\ y/d\right\} \quad . \quad . \quad (16)$$

where y denotes the position of the geometric centre. This equation is an alternative to equation (10) and it is better suited to the application of the correction since the variables on the right-hand side will be known. The traverses made with the fine flat pitot have yielded curves of $\tau_0 y^2/\rho\nu^2$ against $(P-p)\,y^2/\rho\nu^2$ and it is proposed to accept the results from the pipe in the range $y/h > 2{\cdot}5$, $2y/D < 0{\cdot}2$ as being correct. The circular pitots on the wall of the pipe have yielded a curve of $\tau_0 d^2/4\rho\nu^2$ against $(P-p)\,d^2/4\rho\nu^2$.

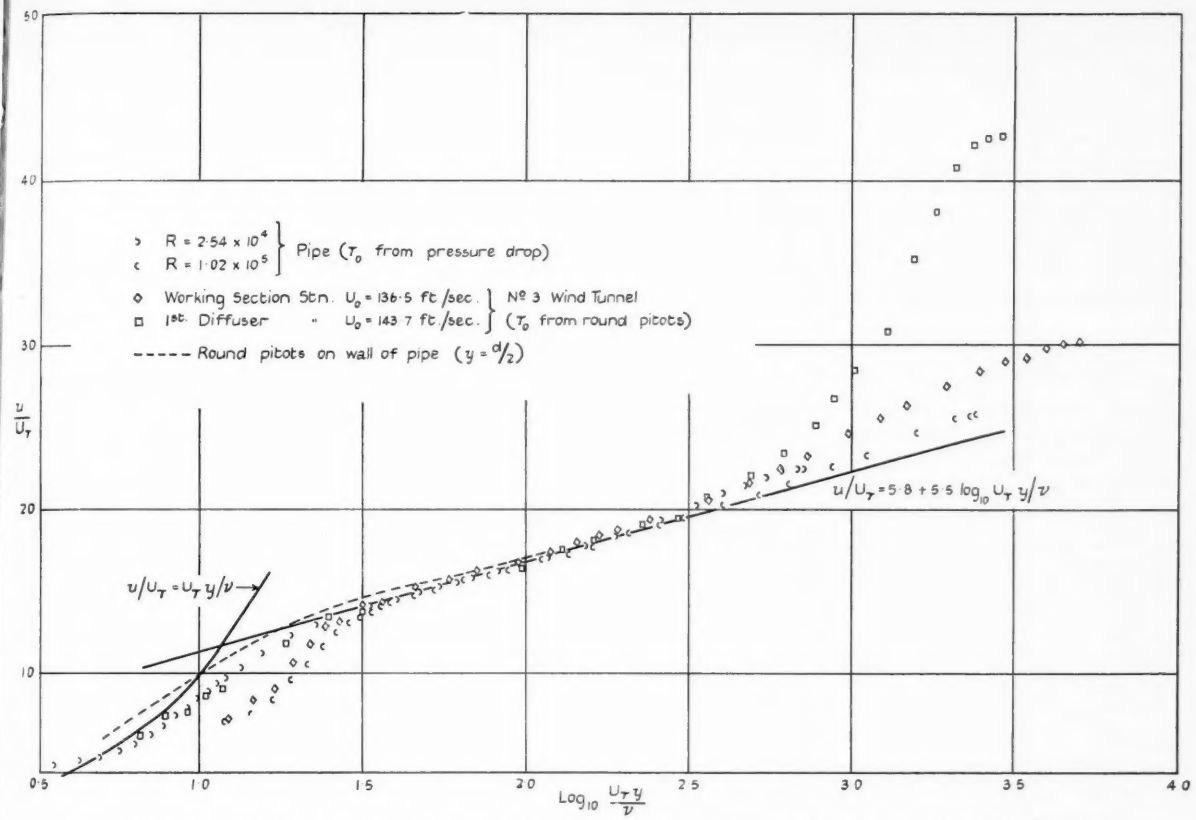

R = 2·54 x 10⁴
R = 1·02 x 10⁵
Pipe (τ₀ from pressure drop)
Working Section Stn. U₀ = 136·5 ft/sec.
1st. Diffuser " U₀ = 143·7 ft/sec.
Nº 3 Wind Tunnel (τ₀ from round pitots)
Round pitots on wall of pipe (y = d/2)
u/U_τ = 5·8 + 5·5 log₁₀ U_τ y/ν
u/U_τ = U_τ y/ν
u/U_τ
Log₁₀ U_τ y/ν

FIGURE 7. Non-dimensional plotting of observations from various pitot traverses (flat pitot). u/U_τ against $\log_{10} U_\tau y/\nu$.

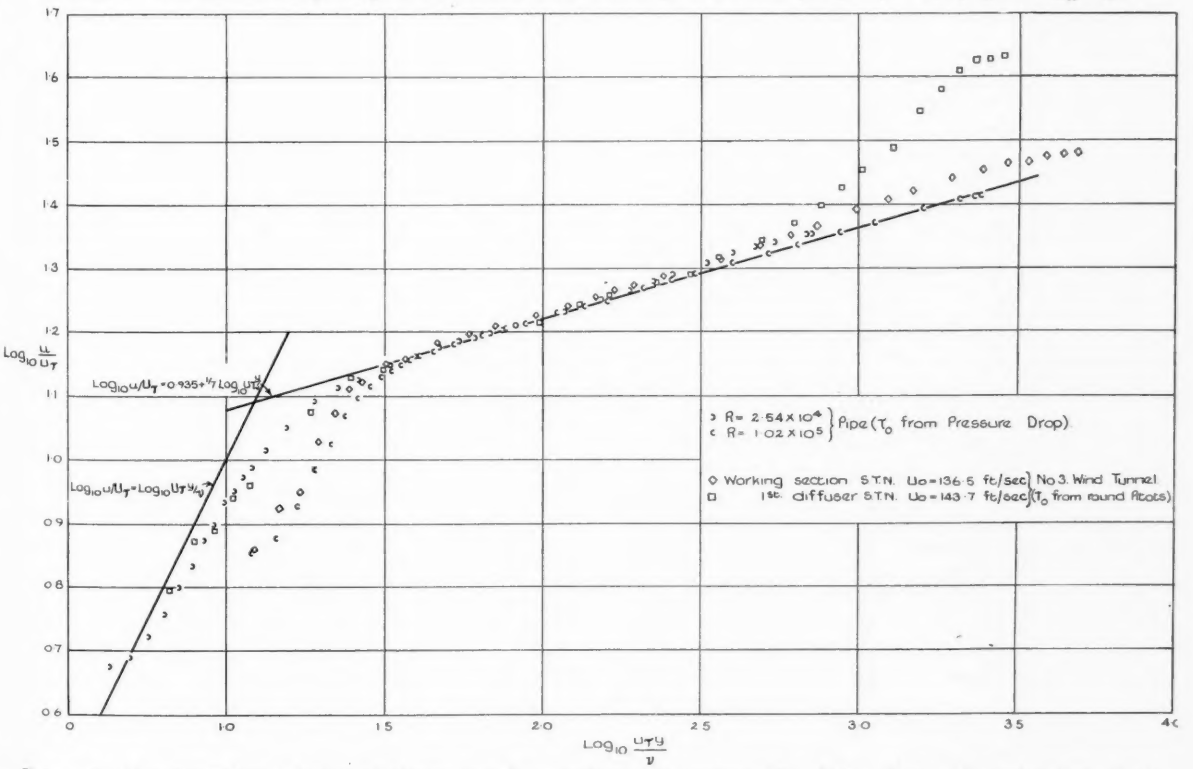

Log₁₀ u/U_τ = 0·935 + 1/7 Log₁₀ U_τ y/ν
Log₁₀ u/U_τ = Log₁₀ U_τ y/ν
R = 2·54 x 10⁴
R = 1·02 x 10⁵
Pipe (τ₀ from Pressure Drop)
Working section S.T.N. U₀ = 136·5 ft/sec
1st. diffuser S.T.N. U₀ = 143·7 ft/sec
No 3. Wind Tunnel (τ₀ from round Pitots)
Log₁₀ u/U_τ
Log₁₀ U_τ y/ν

FIGURE 8. Non-dimensional plotting of observations from various pitot traverses (flat pitot). $\log_{10} u/U_\tau$ against $\log_{10} U_\tau y/\nu$.

To deduce δ from the measurements it is best to plot both sets of observations in the form

$$\frac{P-p}{\tau_0}=\left(\frac{(P-p)\,y^2}{\rho\nu^2}\right) \quad . \quad . \quad . \quad (17)$$

when y refers to the position of the geometric centre. For constant values of the L.H.S. it is then a simple matter to determine δ such that when added to $d/2$ it brings the round pitot results into agreement with the flat pitot results. Alternatively, the results, if plotted in the form suggested by equation (1), *i.e.*

$$u/U_\tau=f\left(\frac{U_\tau y}{\nu}\right) \quad . \quad . \quad . \quad (1)$$

and shown in Figs. 7 and 8 will yield $\bar{\delta}$. For large values of $U_\tau y/\nu$ the flat pitot results and the round pitot results are well represented by power laws with a common index of 1/7 corresponding to the 7/8 index previously mentioned and consequently δ/d tends to a constant value for large values of $U_\tau y/\nu$ or $(P-p_0)\,d^2/4\rho\nu^2$. The results are shown in Fig. 3 curve (*b*) where $\bar{\delta}/d$ is plotted against $(P-p_0)\,d^2/4\rho\nu^2$. At large values of the variable $(P-p_0)\,d^2/4\rho\nu^2$, $\bar{\delta}/d=0{\cdot}12$. For lower values of $(P-p_0)\,d^2/4\rho\nu^2$, $\bar{\delta}/d$ rises and appears to be tending a constant value of about 0·18 in the region corresponding to the viscous sub-layer. These values should be compared with the value of 0·18 obtained by Young and Maas[14] which should be applicable at large distances from a wall. It should be emphasised that the present result for circular pitots on a wall is provisional and research is in hand to determine $\bar{\delta}/d$ for a range of y/d.

The flat pitot can be dealt with similarly, but no attempt has been made to analyse the results obtained here because the error in determining just when the pitot left the wall was about 1/1,000 in. which should be compared to the width of the pitot of 6/1,000 in. Moreover, careful alignment of the pitot wall parallel to the surface is necessary. The present traverses were more concerned with conditions farther out from the wall where the present accuracy is probably sufficient. This idea of a restricted dynamical similarity will form a convenient framework in which accurate experiments may be made as suggested in Section 2. An alternative form to equation (10) in Section 2 is

$$\bar{\delta}/h=f\left(\frac{U_\tau y}{\nu}\,,\,\frac{U_\tau h}{\nu}\right) \quad . \quad . \quad . \quad (18)$$

which is the form which the displacement effect assumes in Figs. 7 and 8. These figures show that the displacement near the wall is of opposite sign to that for circular pitots near the wall, *i.e.* the effective centre is displaced towards the wall. It will be evident that accurate information about the displacement effect for flat pitots will be difficult to obtain because of the difficulty of constructing geometrically similar pitots and, although $U_\tau h/\nu$ is the essential variable, only a restricted range of this can be covered for one pitot by varying U_τ.

8. General Comments

The present experiments establish the existence of a region of local dynamical similarity near a wall in a turbulent boundary layer, which is independent of pressure gradient. On this basis two simple and practical methods of determining skin friction by means of pitot tubes have been evolved. The use of geometrically similar circular pitot tubes resting on the wall is the most accurate method and is most convenient for practical application, both in the laboratory and on aircraft or ships. Alternatively, pitot traverses will also yield the skin friction, but more knowledge is needed about displacement effects before this can attain the accuracy given by pitots resting on the wall. For both methods, knowledge of the extent of the region of similarity is necessary. The experiments described here and Spence's[8] analysis of Schubauer and Klebanoff's[11] data suggest that, for favourable or slightly adverse pressure gradients, this region is about 1/5 of the boundary layer thickness. This is confirmed at much larger Reynolds numbers and much greater values of $U_\tau y/\nu$ by Kempf and Karhan's[12] measurements in the boundary layer of a ship. In adverse pressure gradients, as turbulent separation is approached, this region appears to shrink. In the present experiments with $H=1{\cdot}83$ it is about 1/10 of the boundary layer thickness and analysis of Spence's[8] graphs shows that it is slightly less than this for $H=2{\cdot}0$, and about 1/20 for $H=2{\cdot}4$. At separation ($H=2{\cdot}4-2{\cdot}8$), where τ_0 vanishes, it must be expected that the region will shrink to zero.

The question will probably be asked why it is the shear stress at the wall, τ_0, that proves to be the important variable when, from the linear distribution of shear stress in pipes and the measured shear stress[11] in a boundary layer, it is known that there are considerable variations of shear stress through this region, particularly as separation is approached. The answer would appear to be that existence of the boundary layer itself and the processes of momentum and energy transfer in this region are directly related to the wall shear stress and that this determines the turbulence pattern. Spence[16] has suggested that the distribution of shear stress through the boundary layer is a consequence of the equation of motion and the velocity distribution. He has shown that, if

$$\frac{u}{U_\tau}=f\left(\frac{U_\tau y}{\nu}\right) \quad . \quad . \quad . \quad (1)$$

is assumed to be strictly true, it is possible to compute the shear stress distribution. He has made calculations on this basis which show satisfactory agreement with Schubauer and Klebanoff's[11] measurements. It may be noted that the explicit form of equation (1), *i.e.* equation (4), as deduced by mixing length theory for the outer part of this region, is based on the assumption that the shear stress is constant and equal to the wall value τ_0.

This idea of a restricted dynamical similarity which has been applied successfully to the reading of pitot tubes in this report could be extended to the analysis of other measurements. For example, the reading of a static pressure hole is known to be influenced by hole diameter d', and the depth t of the hole in the wall. Thus if p' is the pressure recorded by a hole of finite diameter and p is the true static pressure at the wall, then by the arguments of Section 2

$$\frac{(p'-p)d'^2}{\rho\nu^2} = f\left(\frac{\tau_0 d'^2}{\rho\nu^2},\ d'/t\right). \quad . \quad (19)$$

This could then form a framework for an experimental investigation to determine the effect of hole size and shape.

The idea might also be extended to quantities which describe the turbulence near the wall. For instance if a length "l" representative of the scale of turbulence were chosen we should expect, on a similarity basis, to be able to write

$$\frac{l}{y} = f\left(\frac{U_\tau y}{\nu}\right), \quad . \quad . \quad (20)$$

a form already familiar from "mixing length" theory but less restrictive in its derivation. Again, turbulence intensity and static pressure variation in this region could be dealt with in the same way on this similarity basis.

So far the investigations have been restricted to smooth or nearly smooth walls. The practical application of the method to the determination of local skin friction for ships will require an investigation of the effects of roughness. For hydrodynamically rough walls, when the skin friction coefficient is independent of Reynolds number, conditions near such walls would be expected to depend only on τ_0, ρ, ε—the roughness height, and a suitable length such as the distance y from the wall. Thus for geometrically similar round pitot tubes on the surface, the equation corresponding to equation (5) for smooth walls will take the form

$$\frac{P-p_0}{\tau_0} = F\left(\frac{d}{\varepsilon}\right) \quad . \quad . \quad . \quad (21)$$

For *slightly* rough walls the existing determination of the form of the function in equation (5) or (5*a*) may be sufficiently accurate, provided that d/ε is large. In other words viscosity is still assumed to dominate the flow at the wall.

Application of these methods of determining skin friction to flight experiments will require a consideration of the effects of compressibility, but a detailed discussion of this is outside the scope of this paper.

9. Conclusions

(*a*) A simple and accurate method has been developed for deducing the skin friction from the readings of geometrically similar round pitot tubes located on the surface. The method should prove useful for full scale investigations of skin friction on aircraft and ships, as well as opening up new fields of investigation in the laboratory.

(*b*) In the development of the method it has been established that there is a region near the wall of the order of 1/10 of the boundary layer thickness, in which conditions depend only on τ_0, ρ, ν and a suitable length. This was suggested by Ludwieg and Tillmann's[7] discovery that the velocity distribution in this region assumes a universal form and further evidence has been produced to support this.

(*c*) This universal velocity distribution, if it can be determined accurately enough, could also be used to determine the skin friction from pitot traverses, provided that the displacement of the effective centre of a pitot tube near a wall can be established.

(*d*) It is suggested that turbulence intensity* and scale and static pressure variations in this region could also be related on a non-dimensional basis using the variables listed under (*b*). In the same way this idea of a local dynamical similarity should provide a framework in which the displacement of the effective centre of a pitot tube and the effect of hole size and shape on the reading of a surface static pressure hole could be investigated.

(*e*) Further investigations into effects of roughness and compressibility will be necessary before the method can be widely applied to full scale measurements.

ACKNOWLEDGMENT

The author expresses his appreciation of the part played by N. B. Surrey in this research. It is largely due to his patience and skill in constructing the geometrically similar circular pitot tubes that the research has been brought to a successful conclusion.

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*Author's Note:—Since this paper was written J. Laufer (The Structure of Turbulence in Fully Developed Pipe Flow, N.A.C.A. T.N. 2954), has produced evidence in favour of this similarity hypothesis close to the wall.

The Analysis of Shear Distribution for Multi-Cell Beams in Flexure by means of Successive Numerical Approximations

by

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1. Introduction

The determination of shear distributions for multi-cell sections can conveniently be considered as two separate problems.

(*i*) the shear flow arising from a pure torsional couple applied in the plane of the section, and

(*ii*) the shear flow arising from a resultant shear force acting on the section so as to produce no resultant twist per unit length of that section, *i.e.* through the shear centre of that section.

Both problems involve finding the value of one unknown shear flow for each cell, so that in multi-cell construction a set of simultaneous equations is obtained, which must be solved to obtain the shear pattern.

The solution of problem (*i*) by successive numerical approximations has been dealt with completely by Benscoter[1]. The present paper gives a method for problem (*ii*).

The usefulness of the method becomes more apparent with increasing numbers of spar webs as may be envisaged for future wing sections of small thickness chord ratios[5]. It is analogous in the procedure used to the Hardy Cross moment distribution method for continuous beams, and has similar advantages. An approximate solution of any required degree of accuracy is quickly obtainable at the design stage and the method is readily adaptable for use by a computer with no knowledge of the structural or mathematical theory involved.

Notation

q_0 basic shear flow for statically determinate section

q_1 closing shear flow for cell (1)

q_2 closing shear flow for cell (2), and so on for each cell

q_1' closing shear flow for cell (1) neglecting the effect of the other cells

q_1'' correction shear flow for cell (1), and so on for each cell

s distance around wall of cells

t thickness of wall

$\Sigma_1 r$ summation of length/thickness ratio around cell (1)

r_{12} length/thickness ratio of web between cell (1) and cell (2)

d_{12}, d_{21} transformation factors associated with cell (1) and cell (2)

$\Sigma_1 q_0 r$ summation of basic shear stress for cell (1) along the walls, and so on for each cell

Originally received 24th May 1953.

2. Theory of Method

The flexural shear stresses in multi-cell box beams are usually calculated by means of the general equation

$$\oint \frac{q}{t} ds = 0 \qquad . \quad . \quad . \quad (1)$$

where the integral is taken around each cell[2]. This equation may be derived from consideration of minimum strain energy and it implies that the twist of each cell is zero. It has been pointed out by various authors[3, 4] that equation (1) is not exactly true, being modified if Poisson's ratio is not zero; however, it is, like the engineer's bending theory, a useful assumption that will probably continue to be used whenever possible.

Consider the centre cell (2) of any three adjacent cells (1), (2) and (3) as shown in Fig. 1. q_0 is the variable basic shear flow in static balance with the applied shear force on the section, and determined by one of the usual methods as described later. q_1, q_2 and q_3 are redundant closing shear flows.

Applying equation (1),

$$\oint_2 q_0 \frac{ds}{t} - q_2 \oint_2 \frac{ds}{t} + q_1 \int_{21} \frac{ds}{t} + q_3 \int_{23} \frac{ds}{t} = 0, \qquad (2)$$

the suffixes "21" and "23" implying integration along the webs only.

Hence from equation (2)

$$q_2 = \frac{\oint_2 q_0 \frac{ds}{t}}{\oint_2 \frac{ds}{t}} + q_1 \frac{\int_{21} \frac{ds}{t}}{\oint_2 \frac{ds}{t}} + q_3 \frac{\int_{23} \frac{ds}{t}}{\oint_2 \frac{ds}{t}} \qquad . \quad . \quad (3)$$

Using the notation previously defined, equation (3) becomes

$$q_2 = \frac{\Sigma_2 q_0 r}{\Sigma_2 r} + \frac{r_{21}}{\Sigma_2 r} q_1 + \frac{r_{23}}{\Sigma_2 r} q_3, \qquad . \quad (4)$$

or, introducing the transformation factor notation,

$$q_2 = q_2' + d_{21} q_1 + d_{23} q_3. \qquad . \quad . \quad (5)$$

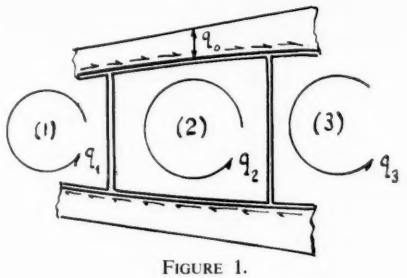


FIGURE 1.

It is seen that q_2' is the value of the closing shear flow required to satisfy equation (1) when the adjacent closing shear flows are zero. Hence first approximations to all the closing shear flows may be made by neglecting the effect of adjoining cells, *i.e.*

$$\left.\begin{aligned} q_1 &\simeq q_1' \\ q_2 &\simeq q_2' \\ q_3 &\simeq q_3' \end{aligned}\right\} \quad . \quad . \quad . \quad (6)$$

By substituting (6) in (5), a second approximation for the value of q_2 is obtained

$$q_2 \simeq q_2' + d_{21}q_1' + d_{23}q_3' \quad . \quad . \quad (7)$$

or

$$q_2 \simeq q_2' + q_2'' \quad . \quad . \quad . \quad (8)$$

where q_2'' is a correction added to the first approximation. Similar corrections q_1'' and q_3'' are made to the approximations for q_1 and q_3. Hence, as a third estimate for q_2 these corrections should be included and (7) becomes

$$q_2 \simeq q_2' + d_{21}(q_1' + q_1'') + d_{23}(q_3' + q_3''). \quad . \quad (9)$$

Thus by repeating the procedure a power series of the transformation factors is obtained which, if taken to infinity, would give an exact solution. However, the series rapidly converges and only a few operations are required in practice.

It is therefore necessary to devise a method to carry out these operations in a systematic routine. This is done in the following manner.

3. Procedure

To illustrate the method a three-cell beam is considered. It has been assumed that the bending end loads are taken by discrete particles, as indicated in Fig. 2(*a*), although any other arrangement may be used. The system of dimensions used in the example is also given in Fig. 2(*a*).

(1) Consider the section cut at the leading edge and the inner webs. This produces in effect a long channel section, as in Fig. 2(*b*), for which the basic shear flow q_0 balancing the resultant applied shear force F may be obtained either from the equation

$$q_0 = \frac{F}{I}\left(\sum_0^s A\bar{y} + \int_0^s yt\,ds\right) \quad . \quad . \quad (10)$$

where A is the flange area, y the distance from the principal axis of the section, XX, and I the second moment of area about XX; or by direct consideration of the rate of change of end load.

(2) Obtain the various constants which are functions of the geometry of the particular section.

$$r_{12} = \frac{s_{12}}{t_{12}} = r_{21}; \qquad r_{23} = \frac{s_{23}}{t_{23}} = r_{32} \quad . \quad (11)$$

$$\left.\begin{aligned} \Sigma_1 r &= \frac{s_{18}}{t_{18}} + \frac{s_{12}}{t_{12}} + \frac{s_{17}}{t_{17}} \\ \Sigma_2 r &= \frac{s_{29}}{t_{29}} + \frac{s_{23}}{t_{23}} + \frac{s_{26}}{t_{26}} + \frac{s_{21}}{t_{21}} \\ \Sigma_3 r &= \frac{s_{3\cdot10}}{t_{3\cdot10}} + \frac{s_{34}}{t_{34}} + \frac{s_{35}}{t_{35}} + \frac{s_{32}}{t_{32}} \end{aligned}\right\} \quad . \quad . \quad (12)$$

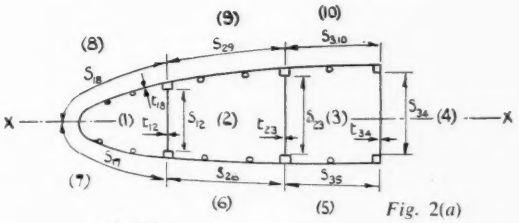


Fig. 2(a)

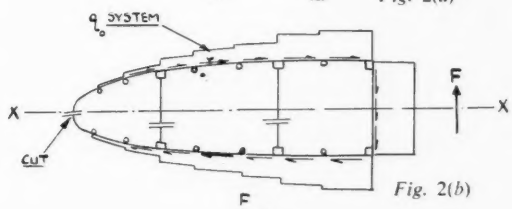


Fig. 2(b)

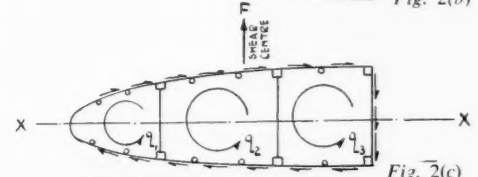


Fig. 2(c)

REQUIRED DATA.	$\Sigma_1 q_0 r$	$\Sigma_2 q_0 r$	$\Sigma_3 q_0 r$
	$\Sigma_1 r$	r_{12} — $\Sigma_2 r$	r_{23} — $\Sigma_3 r$
	d_{12}	d_{21}	d_{23} d_{32}
TRANSPOSE FACTORS	d_{21}	d_{12}	d_{32} d_{23}
1ST APPROXIMATION:	q_1'	q_2'	q_3'
CORRECTION:	q_1''	$d_{12}q_2'$	$d_{21}q_1' + d_{23}q_3'$ $d_{32}q_2'$
CORRECTIONS CONTINUED TO REQUIRED DEGREE OF ACCURACY.	q_1'''	$d_{12}q_2''$	$d_{21}q_1'' + d_{23}q_3''$ $d_{32}q_2''$

SUMMATION: $q_1 = q_1' + q_1'' + q_1''' + \cdots$ $q_2 = q_2' + q_2'' + q_2''' + \cdots$ $q_3 = q_3' + q_3'' + q_3''' + \cdots$.

CHECK BY REITERATION: $q_1 = q_1' + d_{12}q_2$. $q_2 = q_2' + d_{21}q_1 + d_{23}q_3$ $q_3 = q_3' + d_{32}q_2$.

THE FINAL SHEAR FLOW PATTERN IS OBTAINED BY THE ADDITION OF q_1, q_2 AND q_3 TO THE q_0 SYSTEM, AS SHOWN IN FIG. 2(c)

FIGURE 2(*a*), (*b*) and (*c*).

(3) The transformation factors are then obtained from the following ratios:—

$$\left.\begin{aligned} d_{12} &= \frac{r_{12}}{\Sigma_1 r} \\ d_{21} &= \frac{r_{21}}{\Sigma_2 r} \\ d_{23} &= \frac{r_{23}}{\Sigma_2 r} \\ d_{32} &= \frac{r_{32}}{\Sigma_3 r} \end{aligned}\right\} \quad . \quad . \quad . \quad (13)$$

(4) A vertical line is drawn below the centre of each cell as in Fig. 2(*c*). Since the column representing a particular cell is operated on by the transformation factors from the adjacent cells, the initial operation is to transpose the factors as indicated.

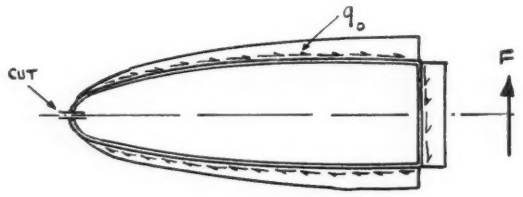


FIGURE 3(*a*).

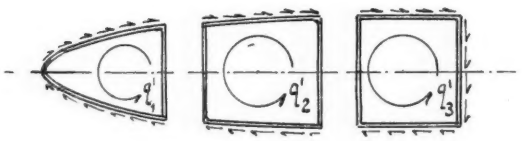


FIGURE 3(*b*).

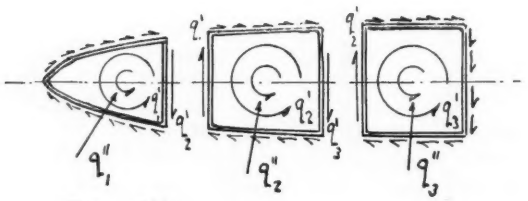


FIGURE 3(*c*).

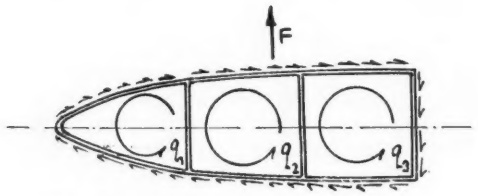


FIGURE 3(*d*).

(5) Determine the first approximations to the closing shear flows from the expressions

$$\left.\begin{aligned} q_1' &= \frac{\Sigma_1 q_0 r}{\Sigma_1 r} \\ q_2' &= \frac{\Sigma_2 q_0 r}{\Sigma_2 r} \\ q_3' &= \frac{\Sigma_3 q_0 r}{\Sigma_3 r} \end{aligned}\right\} \quad . \quad . \quad . \quad (14)$$

These first estimates are written by the vertical lines corresponding to the respective cells.

(6) Multiply each initial estimate by the relevant transformation factor above the column and carry over the product to the adjacent cell. The total correction for an internal cell consists of two numbers (*e.g.* $d_{21}q_1' + d_{23}q_3' = q_2''$ in the example) which are added together and operated on again at the next stage.

(7) The total closing shear flows are obtained by summation of the initial estimate and all the following corrections.
Hence $q_1 = q_1' + q_1'' + q_1''' + \ldots\ldots$. (15)
and similarly for q_2 and q_3.

(8) To check the result of the procedure the following reiteration is advisable.

	d_{21}	d_{12} d_{32}	d_{23}
Values as found by summation of corrections and initial approximation	q_1	q_2	q_3
	$d_{12}q_2$	$d_{21}q_1$ $d_{23}q_3$	$d_{32}q_2$
Initial approximation	q_1'	q_2'	q_3'

Final values: $q_1 = q_1' + d_{12}q_2$; $q_2 = q_2' + d_{21}q_1 + d_{23}q_3$; $q_3 = q_3' + d_{32}q_2$

If there is any substantial discrepancy this reiteration may be repeated. This final procedure ensures the elimination of small numerical errors which may arise in the preceding correction method.

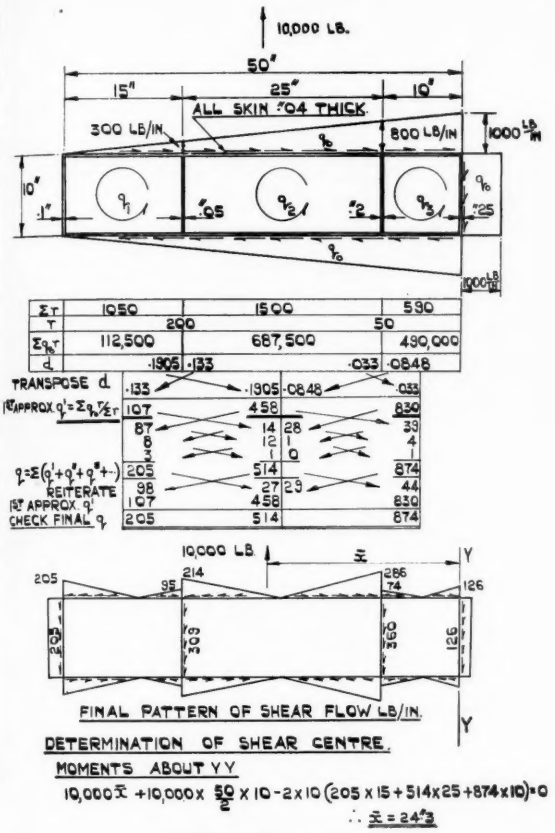
(9) The complete shear flow pattern is obtained by the addition of the closing shear flows q_1, q_2 and q_3 to the basic shear flow q_0.

(10) The position of the shear centre may be obtained by equating to zero the sum of the moments of the applied shear force and the balancing complete shear flows about any convenient point.

4. Physical Interpretation of Method

To help to understand the process, the following interpretation is given.

(*a*) The q_0 system is obtained to balance the shear force F acting on the statically determinate "channel" section, as in Fig. 3(*a*).



EXAMPLE NO. 1.

(*b*) The section is divided into separate cells, each with its share of q_0 shear flow, and closing shear flows are added to each cell to give zero twist (Fig. 3(*b*)).

(*c*) The effect of the shear flows q_1', and so on, on the adjacent cells is considered. They cause small twists which must be balanced by additional closing shear flows q_1'', and so on (Fig. 3(*c*)).

These in turn cause smaller twists on adjacent cells which are in turn balanced.

(*d*) The final system has a set of closing shear flows so that each cell has zero twist (Fig. 3(*d*)).

Since the initial q_0 system balanced the applied force F and finally the section of the beam is untwisted by the force F, it follows that the resultant of the shear flow lies on the shear centre of the section.

5. Special Case of a Two-Cell Beam

In this case no repeated corrections are necessary. The final closing shear flows are given by

$$q_1 = \frac{q_1' + d_{12}q_2'}{1 - d_{12}d_{21}} \quad . \quad . \quad . \quad (16)$$

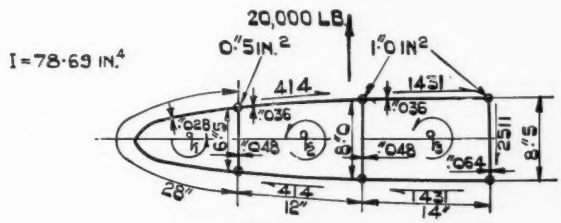
and

$$q_2 = \frac{q_2' + d_{21}q_1'}{1 - d_{21}d_{12}} \quad . \quad . \quad . \quad (17)$$

Hence by carrying out one operation and multiplying both the resulting answers by the factor $1/(1 - d_{12}d_{21})$, the exact solution is arrived at.

6. Examples

Example 1. The first example is a simple rectangular section three-cell box. It has been assumed that the bending end load is taken entirely by the constant thickness skin; the webs, which are of different thicknesses, are shear carrying. These assumptions enable the basic shear flow diagram to be shown simply as triangles for the skins and a rectangle for the web. This type of assumption may be very useful for analysis at the design stage in cases where there are more or less uniformly disposed stringers without large concentrations of end load due to spar flanges. It is seen that the final closing shear flows are obtained by three corrections to the initial approximations. The final reiteration checks exactly. The position of the shear centre is calculated to complete the example.



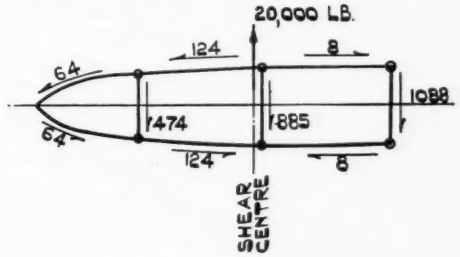
$$q_0 = \frac{F}{I}\Sigma A\bar{y} = \frac{20{,}000}{78{\cdot}69}(1{\cdot}625 + 4 + 4{\cdot}25)$$

$$= 414 + 1017 + 1080 \text{ lb/in AS SHOWN ABOVE.}$$

$\Sigma q_0 r$	0		276,000	1,444,000
Σr	1135		968	1078
r	135		167	
d	·119	·14	·173	·154

TRANSPOSE d	·14	·119	·154	·173
1ST APPROX. q'	0	285		1340
q''	34	0	231	44
	27	5	8	36
	2	4	6	2
	1	0	0	1
$q = \Sigma(q' + q'' + q''' \ldots)$	64	539		1423
REITERATE	64	9	246	83
+ 1ST APPROX. q'	0	283		1340
FINAL VALUE q	64	538		1423

∴ NET SHEAR FLOWS ARE AS FOLLOWS, IN LB./IN.

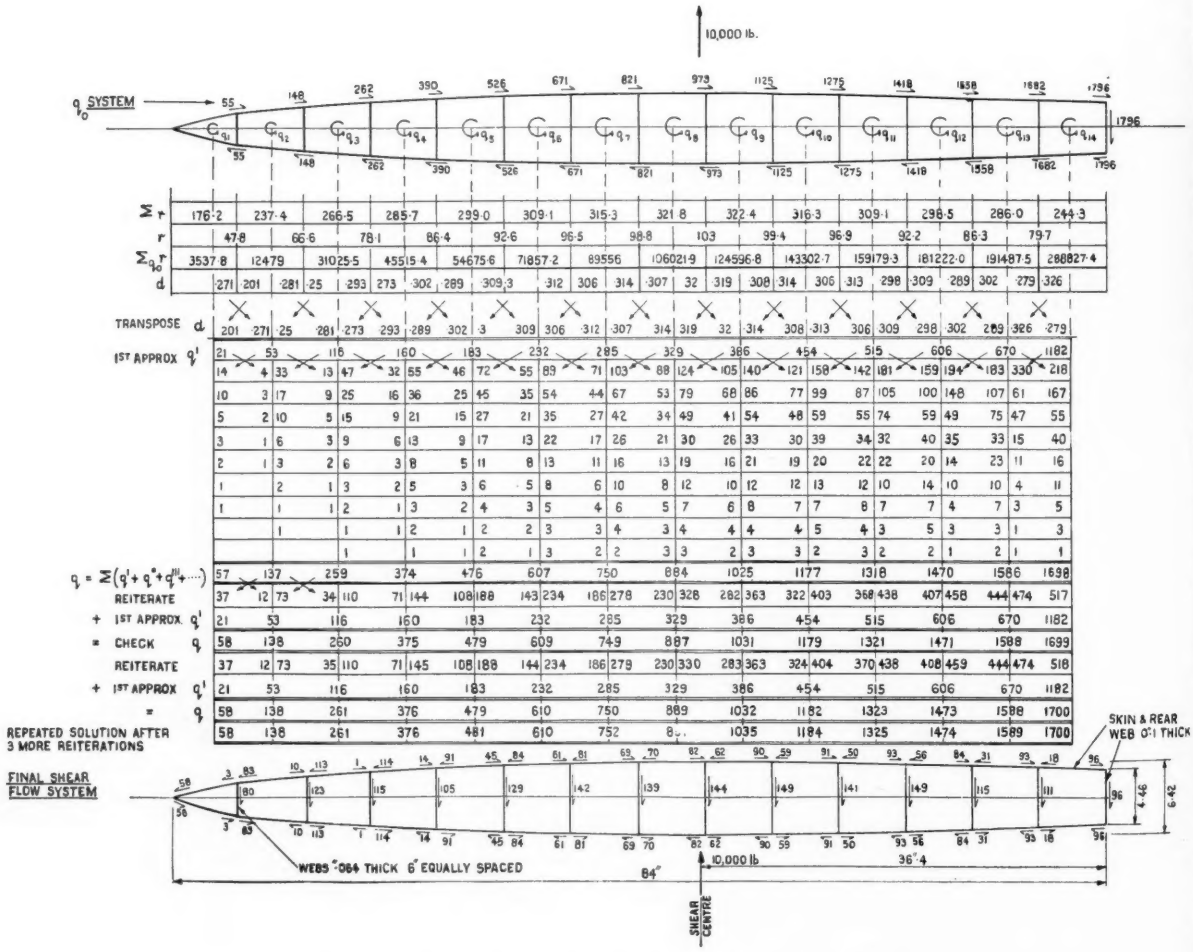


EXAMPLE NO. 2.

CALCULATION OF BASIC SHEAR FLOW q_0 FOR $F = 10{,}000$ LB.

Cell	y	Δs	$y\Delta s$	$\sum_0^n y\Delta s$	y^2	$y^2\Delta s$	q_0/F	q_0
1	1·07	6·42	6·88	6·88	1·145	7·35	0·0055	55
2	1·89	6·15	11·62	18·5	3·57	21·95	0·0148	148
3	2·34	6·09	14·25	32·75	5·48	33·37	0·0262	262
4	2·65	6·06	16·0	48·75	7·04	42·63	0·039	390
5	2·83	6·03	17·0	65·75	8·06	48·4	0·0526	526
6	3·02	6·0	18·13	83·88	9·12	54·72	0·0671	671
7	3·13	6·0	18·75	102·63	9·8	58·8	0·0821	821
8	3·17	6·0	19·0	121·63	10·05	60·3	0·0973	973
9	3·17	6·0	19·0	140·63	10·05	60·3	0·1125	1125
10	3·13	6·0	18·75	159·38	9·8	58·8	0·1275	1275
11	2·98	6·0	17·87	177·25	8·88	53·28	0·1418	1418
12	2·92	6·0	17·5	194·75	8·53	51·18	0·1558	1558
13	2·58	6·0	15·5	210·25	6·66	39·96	0·1682	1682
14	2·38	6·0	14·25	224·5	5·66	33·96	0·1796	1796

$$\sum_0^{14} y^2\Delta s = 625{\cdot}0$$



EXAMPLE NO. 3. Flexural shear distribution for 14 cell beam.

Example 2. In this case a three-cell box is taken in which the end loads are assumed to be in the spar flanges, which are connected by skins and webs capable of carrying shear only. The basic shear flow is obtained from the expression $q_0=(F/I)\Sigma A\bar{y}$. Hence for cell (1) q_0 and therefore q_1' are both zero.

Example 3. The final example is used to illustrate the usefulness of the method with large numbers of redundants. The section analysed is of 5 per cent. thickness/chord ratio and of multi-web design, as may be envisaged for future requirements[5]. The arrangement has 14 cells so that 14 simultaneous equations need to be solved in the usual methods of analysis.

The basic shear flow is obtained from the second term in equation (10), *i.e.*

$$q_0=\frac{F}{I}\int_0^s yt\,ds \qquad . \quad . \quad (18)$$

t is constant around the periphery and the integration has been made for elements of length corresponding to web pitch. Hence the basic shear flow is

$$q_0=\frac{Ft}{I}\sum_0^n y\Delta s=\frac{F}{2\sum_0^{14} y^2\Delta s}\sum_0^n y\Delta s. \qquad . \quad (19)$$

Where y is the mid-ordinate value for each cell. It is assumed by equation (19) that the webs carry shear only.

The solution has been arrived at by making nine corrections to the first approximations, followed by reiteration of the corrected values. Two of these reiterations are shown in detail. After three more it is found that the solution repeats itself exactly with the values given; hence a total of fifteen approximations produces a virtually exact solution. It is interesting to note that after the initial nine corrections the values of the shear flows are within one per cent. of the final values. Hence the full number of approximations would hardly be necessary in practice. One might suppose that at least fourteen approximations would be required to make the effect of cell (1) felt by cell (14). In fact an examination of the solution shows that the effect of cells wide apart upon each other is negligible, as the correction becomes very small in moving across the chord.

7. Conclusions

The method of analysis given reduces a process which can be relatively lengthy and complicated to a simple arithmetic routine that may be carried out by a computer. Its advantages become very great with multi-cell beams of many redundancies, which can be solved without difficulty. Present design trends show that this type of structure may become necessary in the near future. The examples given illustrate the method and indicate other simplifying assumptions that can usually be made. For simplicity they are based on uniform symmetric sections, but the method is applicable to non-symmetric sections and the effects of slope shears may be incorporated.

ACKNOWLEDGMENT

The author expresses appreciation to Mr. R. H. T. Harper, F.R.Ae.S., Chief Structural Engineer of The de Havilland Aircraft Co. Ltd., for permission to publish this paper.

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The First Powered Controlled Flight Fiftieth Anniversary Dinner

A DINNER honouring the Fiftieth Anniversary of the first powered controlled flights—by the Wright Brothers on Thursday 17th December 1903—was held by the Royal Aeronautical Society and the Royal Aero Club on Thursday 17th December 1953 at The Dorchester Hotel, London.

The many distinguished guests and members of both organisations — numbering almost 900 — were received by Sir William Farren, President of the Royal Aeronautical Society, and Miss Mary Farren, and Lord Brabazon of Tara, President of the Royal Aero Club, and Lady Brabazon.

An exhibition of model aeroplanes covering the progress of aviation during the past 50 years was arranged in the reception area and this theme was continued at the Dinner, each of the 90 tables having as its centre piece a model of a British aeroplane.

Sir William Farren presided at the Dinner and after the toast to Her Majesty the Queen, Patron of the Society, read a message which had been received from Her Majesty to mark the historic occasion, together with a message from the President of the Institute of the Aeronautical Sciences. Messages were also received from the Divisions of the Society in Australia and New Zealand and from the Singapore Branch.

The toasts at the Dinner were: "The Memory of the Wright Brothers," proposed by Sir William Farren, and "The First Generation," proposed by the Right Hon. A. T. Lennox-Boyd, Minister of Transport and Civil Aviation. Lord Brabazon of Tara, President of the Royal Aero Club, replied. Verbatim reports of their speeches are given overleaf.

Following the Dinner and the Speeches there was a short interval before the first showing of the film "Powered Flight—the Story of the Century." This film was produced by the Shell Film Unit in co-operation with the Society and involved much research: the idea of the film originated with the Society and work on it began in February 1952 under a special committee of the Society, with Mr. Peter Masefield, Fellow and Vice-President of the Society, and Mr. Peter W. Brooks, Associate Fellow, acting as advisors throughout the making of the film. It forms an invaluable record of aeronautical achievement during the past 50 years and includes shots of the Wrights in Europe, and many of the early pioneers, combat shots of the First World War and many scenes covering most aspects of aviation between the wars, combat, bombing and other scenes from the Second World War and extracts from recent Shell films of the S.B.A.C. Displays. The film is a moving and exciting record of pioneering and achievement and was obviously much enjoyed.

Some of the models exhibited in the reception area at the Dorchester Hotel.

(Courtesy of The Aeroplane)

From Her Majesty The Queen

I send my sincere thanks to the Members and Guests of The Royal Aeronautical Society and The Royal Aero Club dining together to celebrate the 50th Anniversary of Powered Controlled Flight this evening for their message of greetings and for their good wishes to me and my husband, which we much appreciate.

ELIZABETH R.

17th December 1953

To Her Majesty The Queen

The Members of The Royal Aeronautical Society and The Royal Aero Club and their Guests wish to submit to you, as Patron of The Royal Aeronautical Society, their humble duty while gathered together to celebrate the Fiftieth Anniversary of Powered Controlled Flight. On 17th December, 1903, the first heavier-than-air craft was flown by the Wright Brothers at Kitty Hawk, U.S.A. The occasion is being commemorated by a dinner and by the first showing of a film depicting the story of flight over the last half century. They welcome this opportunity of wishing you and His Royal Highness The Duke of Edinburgh God Speed and a Happy and Successful Voyage.

W. S. FARREN
President, Royal Aeronautical Society
BRABAZON OF TARA
President, Royal Aero Club

To the President, Institute of the Aeronautical Sciences, New York

The Members of The Royal Aeronautical Society and their Guests are celebrating jointly with The Royal Aero Club and their Guests The Fiftieth Anniversary of the First Powered Controlled Flight accomplished by your distinguished countrymen, the Wright Brothers. We are all sensible of this great achievement and look forward to wider and wider use of flying as a means of strengthening the good feeling between the nations.

WILLIAM S. FARREN
President

From the Institute of the Aeronautical Sciences

On the occasion of the celebration of The Fiftieth Anniversary of Powered Flight, the Members of the Institute of Aeronautical Sciences extend thanks to Members of The Royal Aeronautical Society and The Royal Aero Club for their greetings. We also look forward to the continuation of the friendly association of our Societies and the maintaining of the bonds of understanding and goodwill between our nations through the Aeronautical Sciences.

C. J. McCARTHY
President

To the Divisions and the Overseas Branch of the Society

The Members of the Society and The Royal Aero Club with their Guests in London commemorating the fiftieth Anniversary of Powered Controlled Flight, send their greetings and best wishes on this memorable occasion. They hope that aviation may look forward to a yet more inspiring half-century of progress for the good of mankind.

WILLIAM S. FARREN
President

From the Australian Division

All Branch Members and Guests assembled in Sydney and Melbourne send greetings and best wishes on this historic anniversary of the first powered flight on this day 1903.

A. V. STEPHENS
Chairman, Council of Australian Division

From the New Zealand Division

Please convey to Members of the Society and The Royal Aero Club a greeting and thanks for their cable. Though opposite you geographically we are with you in the hope that in the next half-century the gift of flight will be used with true wisdom.

C. W. LABETTE
President, New Zealand Division

From the Singapore Branch

Singapore Branch commemorating fiftieth Anniversary of Flight sends greetings.

The Memory of the Wright Brothers

SIR WILLIAM FARREN, C.B., M.B.E., M.A., F.R.S., M.I.Mech.E., F.R.Ae.S.:—

My Lords, Ladies and Gentlemen,

We have met to honour the memory of Orville and Wilbur Wright, and the flights they made this day 50 years ago. It was, I believe, the first occasion on which men flew a machine carrying its own means of propulsion. It marked the beginning of a new epoch in human affairs.

This is a joint celebration of the Royal Aeronautical Society and the Royal Aero Club. The Royal Aeronautical Society was born nearly 40 years before the first flight. It is the oldest aeronautical society in the civilised world, but at 87 we seem to get younger every year, probably because we keep on flying. I believe that we were the first to propose this gathering, but we welcomed the suggestion of our friends of the Royal Aero Club that they should join with us. I confess that I have a purely personal feeling that it would be better if their President were speaking now, and not I. Lord Brabazon has greater claims than I have to speak for British aviation, but he will have the last word this evening.

I would like to say a word of welcome to our guests. We have invited a fair number and I am sure that they will forgive me if I do not mention them by name, but I confess to a deep feeling that I should make one exception. To those of us who have spent a lifetime in aviation, there is one name above all which symbolises what this half-century has been, and it is that of Lord Trenchard. It is a great pleasure to us all to welcome him.

We hoped that the American Ambassador would join us, and he had indeed said he would speak, but he is on his way to America. I take this opportunity to say that, as we honour today the triumph of two great Americans, so we recognise the achievement in aviation of our American friends. We too adventure in the air with some success, and they have been generous in their tributes to our work. What a craftsman values most is the good opinion of a fellow craftsman.

This association of our two societies is a symbol of the alliance between the scientist, the engineer, and the airman. The Wright Brothers combined in themselves all these three elements. Much has been written about their work, and I will spare you a repetition of it. It is as men that I think of them now, in the light of what they did.

Why did the Wright Brothers embark on trying to fly? Many people had tried before and were trying at about the same time; there was a small but growing, and quite respectable, profession of aeronautics. The Wrights were engineers, but their profession was making bicycles. Their interest in flight must have been aroused by something, and we do not really know what it was.

Now most of us have known a queer feeling which drives us to do something which we had no idea that we would ever do, or even that it would be good for us to try; the desire to explore seems to come to people in this way. I think this is what happened to the Wrights. They had no apparent ulterior motive. They were certainly not trying to make a fortune quickly, indeed, they were obviously aware that they might lose more than they could afford, and they had to ration their work accordingly. I think the truth is that there was in them the creative instinct of the artist, and it just happened that the flying machine captured their imagination. There are many of us here who have known a similar experience. It is not unlike falling in love.

If the Wrights were not born aviators, they were certainly born and trained engineers. To me, an engineer is a man who has to make something that works, something that will hold together and not break, something that will run without seizing-up. The engineer's creation is an inanimate thing, but it must be obedient. It must do something which he determines before he sets to work on it. It must not be wasteful. It must give some service that the world needs, and is prepared to pay for.

The engineer's personal reward is first, that the result of his work is used, and last, that he may then be free to turn to the next job.

Nowadays the mechanism of life is so complicated, that there are many kinds of engineers. But 50 or 60 years ago it was recognised, and I think it was a good thing, that there was one common ground from which all engineering started, and that was an understanding of what we call mechanics, broadly speaking the explanation of how the world works. The Wrights were unquestionably natural engineers of the highest ability, but I feel sure that in their youth they had been soundly trained in the principles of mechanics.

The combination of the artist and the trained engineer is a formidable one. When there is added what we call the scientist, something remarkable is bound to happen. To such people cheap distinctions between theory and practice are without significance. They are essentially experimenters. " Practice " is what they observe, "Theory" the explanation which they seek, which will bring their observations into agreement with the facts of life as they know them. There are occasions when no explanation can be found into which a new observation will fit, and we have almost come to expect one each morning with our daily paper. But the Wrights were working in a field where they did not feel there was anything really mysterious. Hitherto there had been little but guess-work, apart from efforts to copy nature's own solutions by machinery, a method which has never proved successful in any field of human discovery. After all, the Wrights' own excellent bicycles ran, not on legs and feet, but on wheels. Their work was inspired by the scientist's passion to discover the reasons for what they observed, and to prove by experiment that their understanding was wide and deep enough to enable them to advance with confidence to their objective. Some may hold that they were not trained in the methods of science as these are now defined. If so,

Courtesy of The Aeroplane

Sir William Farren and Marshal of the Royal Air Force, The Viscount Trenchard.

we had better look to our definitions. To my mind Orville and Wilbur Wright were good scientists.

The history of what the Wrights did is not always easy to follow, because they were men of few words and preferred to walk by themselves. They were like the cat in Rudyard Kipling's "Just-So Story." But, to borrow a few words from that story, they made the first flying magic in the world. My own belief is that there was concealed within them the fire that burns in the breasts of all who fly for the love of it, and find in flying something for which there is no parallel in human experience. They were the first true airmen. Unless they had become airmen, they could not have completed their task because a great part of their experimental work was done in flight. They were, for many purposes, their own measuring instruments. In the end they became masters of their craft, scientists, engineers, airmen and artists combined.

If my conception of what Orville and Wilbur Wright were is true—and I have little doubt that it is—we should not be surprised that they succeeded. It may be said that they had or needed luck. But what we call "luck" in such adventures as theirs is the power to recognise the jade Opportunity as she flits by, to seize her before she vanishes or falls into the arms of others. Vision, insight, patience, judgment, courage—they had them all. They are famous men.

My Lords, Ladies and Gentlemen, I invite you to rise and salute their memory.

Introducing Mr. Lennox-Boyd, who proposed the toast of "The First Generation" Sir William said:—

Mr. Lennox-Boyd is Minister of Civil Aviation. He is also Minister of Transport and we welcome him in both capacities. I cannot imagine a more difficult task —apart, possibly, from the tasks of the other Ministers concerned—than he has had to do in the past few days. I can say that from the bottom of our hearts, we thank him for what he has done towards giving us the prospect of a happy Christmas.

It has been my good fortune this evening to sit next to Lady Patricia Lennox-Boyd. From her I have gathered some idea of what life has been like for him lately. Even today, and until a few minutes ago, he expected to have to return to the House of Commons at this very moment. I am glad, and I know you all are, that he can now relax a bit, and it is with the greatest pleasure that I ask him to speak to the toast "The First Generation."

The First Generation

THE RT. HON. A. T. LENNOX-BOYD, M.P. (Minister of Transport and Civil Aviation):—

It is a great pleasure to come to such a company and on such an occasion, and I am most deeply grateful to the Royal Aeronautical Society and to the Royal Aero Club for asking me to be here tonight. If I have played a part in bringing about a measure of industrial tranquillity at Christmas, I think it is very charitable of the aircraft world to thank me for it, for I can imagine nothing which would have driven people more into the air than if things had gone the other way. I am also Minister of Shipping, and that opens up a lot of other interesting possibilities. But, anybody this Christmas can go any way they like anywhere they like, provided they can afford it and provided that other countries allow them to enter there; and it is not for me to say which is the most expensive form of travel.

It is indeed a very great privilege to come here this evening and to propose this particular toast; indeed, I cannot imagine a more grand opportunity than that which has been given me.

Now, ladies and gentlemen, I think it was in 1943—I am never quite certain about my dates—that Orville Wright sent a message to the Royal Aeronautical Society. But Wilbur had sent a much earlier message. Forty years ago Wilbur said:—

> "At a time when flying was little thought of in the world, some of the citizens of England banded themselves together to form this Society; and through all the years which have followed, during times when any talk about flying was considered ridiculous and all the people who thought about it were laughed at, this Society met every season."

That is a pretty good tribute, because there is nothing more difficult in our country, I think, and that probably goes for most civilised countries, than to do things that other people think slightly ridiculous.

Tonight we meet to do honour to people, some of whom, thank God, are still here and can answer for themselves, and others who are no longer here, and he would be a very strange person who would be indifferent to the privilege of proposing the toast to "The First Generation." I certainly do so with pride and with humility. They had many difficulties with which to contend. Their successors have difficulties created by man as well as by nature; and I am conscious that I am one of the creators of the more modern difficulties. But we are dealing tonight with a really spectacular achievement, an achievement unique in human history. I have read, as probably most of you have done, the remarkably interesting article in the Journal of the Royal Aeronautical Society by Captain Laurence Pritchard. That is something worth keeping, and I propose myself always to retain it. He discovered in Burton's "The Anatomy of Melancholy," written three or four centuries ago, the suggestion that "if the Heavens then be penetrable, and no lets, it were not amiss to make wings and fly up; and some new-fangled wits, methinks, should some time or other find out."

Tonight we meet to do honour to those "new-fangled wits" who gave all they had, frequently their lives and often their fortunes, to conquer the air. Tonight we can pay our tribute with genuine sincerity to those who have conquered the air and who, by conquering it, as they themselves know, have opened up new problems which their children will have to conquer.

Sir William Farren has said that I am also Minister of Transport. No one who is responsible ultimately for the good government of the transport world can fail to see a curious pattern running through the history of the centuries. Every generation produces a new form of transport which is vehemently opposed by those who are already there. For example, when the coaches first appeared and drove out the pack horses, the long wagons with the great horse teams, there was immense opposition. When addressing an audience a month ago at Gatwick I reminded them of the argument used by Mr. Cresset in 1672, when watching the disappearance of the pack horses and the arrival of the coaches. He said "These coaches and these caravans are one of the greatest mischiefs which have happened of late years to our Kingdom, destroying the breed of good horses, the strength of the nation, making men careless of attaining good horsemanship, a thing so useful and commendable in a gentleman, hindering the breed of watermen, the nursery for seamen and the bulwark of our nation, and lessening His Majesty's revenue."

Then came the canals, to take charge of the rivers. When Mr. Brindley, the great canal man, came before a House of Commons Select Committee, someone said: "Now, Mr. Brindley, what do you really think the rivers are for?" He said: "Of course, to supply the canals with water."

Then came the railways; and the canals had to look out. Then came the roads; and both road and rail have had to look out. I have had to look out about both in the last 48 hours!

Then came air transport; and surely, of all the forms of transport, none has the same miraculous history as this. We have the exhibition, to which we hope to take our children, at the Science Museum at South Kensington. Surely no form of transport and no other achievement in the world could ever produce such a remarkable demonstration of careful thought and planning and of actual achievement through the last half century as that exhibition shows.

We owe a debt to the past, to the psalmist who sighed for the wings of a dove, to immortals like Hermes and to mortals like Perseus, to Daedalus, and to his son Icarus, and the great labyrinth in Crete, from which one could only get out by taking a helicopter! All through the centuries people have dreamed of the conquest of the air. But the problems are not yet solved.

Tonight we think in particular of those who played their part in the first generation, and played it in Great Britain. Yesterday I was looking at a copy of "The Aeroplane" of 1916, which recounted the story of the first generation. There was A. V. Roe, whom it was stated in this edition was the first British subject to fly in Great Britain. There were Claude Grahame-White and Geoffrey de Havilland, F. Handley-Page and Harold Perrin, of the Royal Aero Club. The work of the women makes a long and honourable story; Mrs. Hewlett was the first among the gallant women pilots of Great Britain. Again, Sir Tom Sopwith, and Mr. Sigrist, the Chief Engineer and Manager of his great firm; the Short Brothers; and Holt Thomas, who made a unique contribution. All of them, and many others whom I cannot mention, paved the way for those who followed, the craftsmen and workers who by brain and hand have made our present achievements possible.

I would like to join with Sir William in saying what a pleasure it is to all of us to see Lord Trenchard, the architect of the Royal Air Force, present tonight.

In the field of civil aviation we speak of Sefton Brancker, and of those in the Ministry of Civil Aviation, now part of the Ministry of Transport, who for years have given disinterested service in that field.

This is not only a national achievement; indeed, the anniversary we commemorate would drive out any nationalism today. It is an international field, in which we have played a very honourable part. And our thoughts tonight of the pioneers must go to the Wright Brothers, of whom Sir William has spoken so feelingly —and to others like Samuel Franklin Cody, the American who liked the air over Farnborough so much that he became a British subject. He flew 496 yards at a height of 50-60 ft.

Of this great company, no one is more distinguished than Lord Brabazon, who is to reply to this toast. As Minister of Transport I have often been asked to give people special numbers for their motor cars. It is true

that I have got MYY 1 on my car. As my wife gave me the car, it should really be OUR 1. But no number is more deserving than that which Lord Brabazon managed to get somehow, FLY 1. He was the first aviator to fly a mile around a closed circuit, in a British aeroplane. I think we can say that if this generation has produced an Elizabethan figure in the true sense of the term, it is Lord Brabazon himself. He could live with any of the heroes of the first Elizabethan age; he could drive with them, fly with them, he could explain to them about the Air Registration Board, he can carry on four simultaneous games of chess by correspondence, he can make and fly our boomerangs and can beat any immortals on the Cresta run. He is as young as any man in the present generation, and he knows also the tragedy to which aviation could reduce the world if it passed into unclean hands. "Were Wilbur here," wrote Orville Wright in 1943, "he would be shocked at the havoc which the aeroplane has wrought; but I believe, with slight variation, the old saying still holds good, that he that useth the sword shall die by it, and that we can now look forward with confidence to the post-war era."

That must be the prayer of us all. In the work that Lord Brabazon is doing to see that civil aircraft fly safely and fly cheaply all over the world he is playing his part in trying to ensure the use of this superb invention for the common good of mankind.

Courtesy of The Aeroplane

Lord Brabazon of Tara, President of the Royal Aero Club, responding to the toasts.

The Wright Brothers and the First Generation

LORD BRABAZON OF TARA, G.B.E., M.C., P.C., Hon.F.R.Ae.S. (President of the Royal Aero Club):—

A great dinner like this can only be a success if it has a representative of the Government of the day speaking, as well as the head of all aeronautics, in the person of the President of the Royal Aeronautical Society. We have these two gentlemen here, and we thank them very much for the admirable and wonderful speeches they have made to us.

I am here tonight as the President of the great Royal Aero Club, and it is my duty on its behalf to reply to the toast of "The First Generation."

I dare to speak for the human side, for through our portals every one of that generation has passed. We knew them all; we knew them at the bar, we knew them at lunch, we talked over every subject in the world with them and we knew them all well. We knew the Wrights. They came to our funny little Club of those early days, and we entertained them with the modest ability that was our lot in those days. They appealed to us enormously for they were such quiet and unassuming men. Wilbur we knew better than Orville, because in 1908 Wilbur flew in Europe while Orville flew in America. I was privileged to see Wilbur working and flying at Le Mans. I can see him now in his shed, which was his hotel, where he slept and had his bath. A curious man, very gaunt to look at, always very polite, but rather aloof. He was always ready to talk to anybody who was really keen on the subject, but he was indeed chilly and off-hand if anybody appeared to consider him or aviation a curiosity.

His great friend was Griffith Brewer. Griffith Brewer was one of our greatest friends in the Royal Aero Club; one might look upon him almost as one looks upon Boswell relative to Dr. Johnson. They both enjoyed each other's company right from the very beginning. They were two people very alike, and the height of their happiness was to be in each other's presence and neither of them speaking a word. There was a bond of sympathy between Griffith Brewer and the Wright family which lasted to the very end, and Orville always had a room reserved for Brewer in his modest home in America until his dying day.

It is sometimes asked, what sort of men were these Wrights? I can answer that straight away. You will find the equivalent in any provincial town in this country in the men who sell bicycles and gramophones, people with a certain technical knowledge, able to do most jobs with their own hands, and with keen imagination. They were what you may call today, I suppose, technologists. Sir William Farren has asked why they

ever became keen on aeronautics. I think it was because when they were boys they flew kites, they made a kite which was better than those of the other boys, and sold their kites. They made bicycles and they even raced bicycles; both Wilbur and Orville Wright won races on their own bicycles in order to sell them.

I do not believe that either one of them would have succeeded without the other, for they were so remarkable a team, one checking the other during their work. But I hope you will appreciate what a long up-hill struggle it was for them. They were handicapped by lack of money and lack of time; and, as with all those early pioneers, the whole world looked upon them as cranks, as rather like somebody who was trying to find perpetual motion. I think few of the modern generation realise what lack of faith there was in the possibility of flying only fifty years ago. I had the privilege of introducing Voisin to Wilbur Wright. Voisin was the man who made the machine on which Farman won the Archdeacon Prize. It was a memorable meeting. They grinned at each other the whole way through lunch, neither being able to speak a word of each other's language. While they were having their meal the great Lebaudy airship came over the hotel, and we all ran on to the roof and watched it. Everybody waited for what the French call the "Beau mot juste," and Wilbur Wright said: "How very lucky to have seen that."

This man never pretended to be the great man he was, he never tried to sell himself, he never thought that he was a tremendous personality. He always remained the simple quiet soul that he was; and yet his name and that of his brother will be revered for ever.

I remember asking him a silly question—would he design me a machine to do 100 miles per hour—which was quite a lot to ask at that time. He said "That is quite possible, if you will provide the engines." What a wise remark! "If you will provide the engines" is still the answer to speed today.

The Wright Brothers had a corner in their hearts for England. We always treated them well; for we always treated them, not as exhibits, but as friends. As you know, the Science Museum had the honour of housing their wonderful first machine for 25 years. I saw it again the other day in Washington. I thought it was curious that no mention of its stay here for 25 years was made. The reasons are deep; they do not reflect very great credit upon the Smithsonian Institution. In that fight, where the prophet was without honour in his own country, Griffith Brewer played an honourable, courageous and noble part.

The great Sir George Cayley, when he was studying and making one of his first gliders, suddenly received a letter from Stringfellow, with a most elaborate design which Stringfellow had put down on paper, with steam engines, in fact a machine for carrying many people. The old man was very annoyed and wrote a remarkable letter, in which he wrote: "Really, you must go slow. I do assure you that before flight becomes safe, a hundred necks will be broken." Now for an under-statement this prophecy is a classic.

At what cost in human life have we reached the present position, starting with the death of the great Lilienthal, almost the pioneer of really serious flight. The runway of aviation is paved with tombstones beneath which lie the poor crushed or burned bodies of young, lovable, imaginative, adventurous spirits, the pioneers who fell by the wayside. We shall not forget them, I hope, at this dinner tonight. To take only two, Pilcher and Rolls, what a lot we have missed because flight claimed them so early!

You may well ask what sort of men were those who were the pioneers of flight, and of what did they dream for the future? Why did they do it? They were of all sorts, they came from every walk of life; they persevered, unsupported and alone. Please remember that officially science left them severely alone. They were surrounded by much ridicule. But let me assure you that they did not carry on for any money there was in it—if there were any money in it. They realised that here was something tremendous for mankind. In the various talks of those days which press upon my memory, when we talked among ourselves and dreamed dreams of the future, I cannot remember anybody ever visualising that one would be able to fly from London to New York and back again in 24 hours. That is the tribute I pay to the amazing development that has occurred in these 50 years. Those pioneers all had in their hearts a feeling that they were bringing something good into the world. The point is, were they right?

There was a time when the gift of flight was wholly prostituted for war. It was inevitable, it was correct; and when we took the job on in this country right well we did it. But we must remember that at one time even the word "aeroplane" stank in the nostrils of all decent men throughout the world for a more devastating, death-dealing machine had never been invented. I wondered sometimes whether the work of the Wright Brothers and other early pioneers would not one day be execrated, not celebrated, throughout the world. I wondered whether the ingenuity of man had not produced a juggernaut that would destroy the very civilisation of which it was an expression.

We still hold in our hands such terrible force. It was not for this that pioneers so cheerfully laid down their lives. What was it, then, that they hoped for? I think they hoped that what would happen was what I think is happening now. They hoped that by the fruits of their labour the world would be shrunken in time of separation, as indeed it is. They hoped that within all countries throughout the world there would be services of aeroplanes, and that as they flew back and forth they would, so to speak, serve as a shuttle that would weave a fabric of better understanding and peace throughout the world.

This is beginning to happen today. Will you, Mr. Minister, remember this in your work, and may it indeed inspire you in the future of your great and useful life, that only if that side wins through, will those who brought flying into being be convinced and satisfied that all their efforts were not in vain.

THE following is a list of the model aeroplanes kindly lent for the Fiftieth Anniversary Dinner by the aircraft firms named and the Science Museum, South Kensington:—

ARMSTRONG WHITWORTH AIRCRAFT LTD., SIR W. G.

Argosy	Ensign
Atalanta	N.F. 11
Atlas	Siskin
A.W. 52	Whitley

AUSTER AIRCRAFT LTD.

Auster J.5B	A.O.P. Mk.6

BLACKBURN AND GENERAL AIRCRAFT LTD.

1909 Monoplane	Firebrand
B.2. Trainer	Lincock
Dart	Ripon
Skua	

BOULTON PAUL AIRCRAFT CO. LTD.

Balliol T.1	P.111
T.2	P.120

BRISTOL AEROPLANE CO. LTD.

Blenheim	Bulldog
Boxkite	Freighter
Britannia	Freighter F2B

DE HAVILLAND AIRCRAFT CO. LTD.

Airspeed Ambassador	D.H.4A
Airspeed Consul	Mosquito
Comet, D.H.88	Moth
Comet, D.H.106	Original D.H. (1908)
Wright Biplane	

ENGLISH ELECTRIC CO. LTD.

Canberra	Wren

FAIREY AVIATION CO. LTD.

Campania	Fox
Fantome	Gyrodyne
Firefly	Long-range Monoplane
Swordfish	

GLOSTER AIRCRAFT CO. LTD.

Bamel	Meteor 7
E 28/39	Meteor 8
Gladiator	Meteor 9
Javelin	Meteor 10

HANDLEY PAGE LTD.

O/400	Hinaidi II
O/700	Military Trials Machine
Gugnunc	(1912)
Hanley	Victor
Harrow	W.8
Hermes V	Yellow Peril

HAWKER AIRCRAFT LTD.

Batboat	Hurricane
Camel	Nimrod
Fury Biplane	Sea Hawk
Hart	Tabloid
Hunter	Triplane
Typhoon	

F.G. MILES LTD.

Aerovan	Libellula
Gemini	Messenger
Monarch	

PERCIVAL AIRCRAFT LTD.

Mew Gull	Provost
Prince	Provost Jet Trainer
Proctor V	P.74 Helicopter
Q.6	

A. V. ROE AND CO. LTD.

Anson	Vulcan
Lancaster	504K
Tutor	707A

SAUNDERS-ROE LTD.

London	Skeeter
Princess	SR/A.1

THE SCIENCE MUSEUM

Bamel Racer	D.H.2
Bristol Fighting Scout	Lee Richards Annular
Monoplane	Supermarine S.5
Cody's First British	Supermarine S.6
Army Aeroplane 1	Wright Biplane

SCOTTISH AVIATION LTD.

S.E. Pioneer	Twin Pioneer

SHORT BROTHERS AND HARLAND LTD.

Empire Boat	Sealand
S.A. 4	Solent IV
S.B.5	Sturgeon I
S.B.6	Sunderland

VICKERS-ARMSTRONGS LTD.

Gun Bus	Viscount
Valiant	Wellesley
Vimy	Wellington

VICKERS-SUPERMARINE

Attacker	Spitfire
Seafire 47	Stranraer
Seagull	Swift
Walrus	

WESTLAND AIRCRAFT LTD.

Dreadnought	Original Seaplane
Everest P.V.3	Pterodactyl
Lysander	S.51 Helicopter
Whirlwind	

THE FOLLOWING is a list of those who accepted invitations to the Dinner and, in so far as it is possible to ascertain, those who were present:—

Mr. and Mrs. C. Abell, Mr. and Mrs. C. F. Abell, Mr. and Mrs. J. W. Adderley, Mr. and Mrs. Paul Adorian, Mr. and Mrs. John Aherne-Heron, Wing Commander and Mrs. B. T. Aikman, Group Captain and Mrs. Airey, Captain and Mrs. M. R. Alderson, Mr. M. F. Allward, Mrs. H. R. Ambrose, Mr. and Mrs. Leonard Richard Ambrose, Captain and Mrs. Lewis Robert Ambrose, *Anglo-American Aviation News Agency* London Editor, Wing Commander and Mrs. R. F. Anstead, Vice Admiral Sir Edmund W. Anstice, Mr. L. S. Armandias, Squadron Leader and Mrs. W. H. Armstrong, Air Vice-Marshal R. L. G. Atcherley, Mr. and Mrs. W. S. Ault, Mr. F. P. Ayers, Mr. R. F. Ayers, Captain E. D. Ayre.

Mr. and Mrs. L. Bagrit, Dr. and Mrs. G. M. Bailey, Air Chief Marshal Sir John W. and Lady Baker, Dr. and Mrs. A. M. Ballantyne, Mr. and Mrs. John M. Ballard, Mr. J. Bamford, Air Commodore and Mrs. F. R. Banks, Miss Banks, Mr. A. H. Barber, Miss B. M. Barlow, Sir James H. and Lady Barnes, Mr. A. J. Barrett, Mr. and Mrs. B. C. Barrington-Mason, Captain K. J. G. Bartlett, Mr. R. Bartram, Miss F. Barwood, Mr. and Mrs. E. L. Bass, Commander and Mrs. F. W. N. Bassett, Wing Commander and Mrs. R. P. Beamont, Mr. A. W. Bedford, Mr. and Mrs. W. O. Beer, Mr. and Mrs. John Bell, Air Vice-Marshal and Mrs. D. C. T. Bennett, Mr. V. Bennett, Mr. S. C. Bentley, Squadron Leader W. Bentley, Mr. and Mrs. F. Besançon, Captain F. A. Best, Mr. J. D. R. Bethell, Mr. and Mrs. E. Beverley, Group Captain and Mrs. Nino Bianchi, Mr. and Mrs. L. H. N. Bickmore, Mr. and Mrs. R. E. Bird, Mr. and Mrs. Robert Blackburn, Mr. and Mrs. E. W. Bonar, Mr. R. H. Bound, Mr. A. B. Bourne, Mr. E. C.

Bowyer, Lord and Lady Brabazon of Tara, Mrs. Joan Bradbrooke, Wing Commander J. R. T. Bradford, Mrs. M. E. Branch, Dr. L. G. Brazier, Mr. M. J. Brennan, Miss R. Bridgman, Mr. Leonard Bridgman, Mr. K. F. Bridle, Mr. and Mrs. W. Brierley, *British Broadcasting Corporation* Facilities Unit, Mr. D. T. Broadbent, Mr. and Mrs. P. W. Brooks, Mr. D. L. Brown, Wing Commander H. H. S. Brown, Mr. and Mrs. K. F. Brown, Sir Sam and Lady Brown, Air Commodore Sir Vernon and Lady Brown, Miss Daphne Brown-Kelly, Mr. W. Browning, Mr. and Mrs. G. R. Bryce, Sir John and Lady Buchanan, Mr. and Mrs. H. Budd, Mr. and Mrs. H. J. Budd, Mr. and Mrs. P. W. S. Bulman, Mr. and Mrs. C. R. Burgess, Mr. D. Burrell, Mrs. E. C. M. Burrell, Mr. and Mrs. H. Burroughes, Mr. E. J. Bush, Mr. Victor Butler, Mr. and Mrs. Francis Butters, Mrs. B. Buxton.

Air Commodore and Mrs. C. S. Cadell, Sir Sydney and Lady Camm, Mr. and Mrs. A. C. Campbell Orde, Mr. I. R. Cantle, Mr. H. Caplan, Mr. A. Carter, Mr. and Mrs. C. S. Carter, Air Commodore and Mrs. D. W. Bonham Carter, Sir Maurice Bonham Carter, Mr. S. R. Cauthery, Mr. and Mrs. Francis Chichester, Air Vice-Marshal and Mrs. C. E. Chilton, Dipl. Ing. T. L. Ciastula, Mr. and Mrs. C. W. Clark, Mr. A. C. Clarke, Mr. D. A. Clarke, Mr. A. V. Cleaver, Mr. and Mrs. A. N. Clifton, Sir Alan and Lady Cobham, Mr. Michael J. Cobham, Miss Harriet Cohen, Professor and Mrs. A. R. Collar, Squadron Leader W. Collett-Mason, Air Vice-Marshal Sir Conrad Collier, Mr. W. R. Collingwood, Mr. and Mrs. Collins, Mr. and Mrs. A. E. Collins, Mr. E. W. Collins, Major and Mrs. A. Q. Cooper, Mr. H. J. Cooper, Major and Mrs. J. L. B. H. Cordes, Air Chief Marshal Sir Alec and Lady Coryton, Air Commodore M. Costello, Mr. and Mrs. William Courtenay, Miss Ann Courtenay, Mr. and Mrs. C. L. Cowdrey, Mr. and Mrs. Hedley S. Crabtree, Mr. and Mrs. R. J. P. Crawfurd, Lieutenant Commander and Mrs. R. A. Creerey, Sir George Cribbett, Colonel and Mrs. A. T. Culbertson, Sir William and Lady Cushion, Mr. and Mrs. R. C. Cussons, Miss Diana Cuzner.

Mr. E. G. Davidson, Mr. and Mrs. B. D. Davies, Mr. and Mrs. S. Kenneth Davies, Mr. and Mrs. Edward Davis, Mr. J. H. Davis, Mrs. Graham Dawbarn, Lord and Lady De l'Isle and Dudley, Lieutenant Colonel Harry Delacombe, Mrs. W. C. Devereux, Major and Mrs. Norman Dicks, Air Chief Marshal Sir William and Lady Dickson, Mr. and Mrs. F. A. Dismore, The Marquis of Donegall, Mr. Geoffrey Dorman, Marshal of the Royal Air Force Lord Douglas of Kirtleside, Lady Douglas, Dr. G. P. Douglas, Mrs. G. P. Drake, Mr. L. Drucquer, Mr. and Mrs. J. G. N. Drummond, Squadron Leader and Mrs. Neville Duke, General Guy du Merle, Mr. A. Dunn, Mr. and Mrs. R. W. Dunn, Mr. J. A. Dunsby, Mrs. John Dykes.

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TECHNICAL NOTES

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The Centre of Shear for Sections Bounded by Two Circular Arcs

by

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IN TWO RECENT NOTES[1, 2] Jacobs and Duncan considered the St. Venant torsion and flexure problems for beams of aerofoil cross section and have given methods for determining the centre of shear once the torsion function for the section has been found. The purpose of the present note is to give results for the location of the centre of shear for a limited range of cross sections bounded by two circular arcs for which the torsion function has long been known[3]. The calculations shed some light on the relative influence of camber and thickness on the location of the centre of shear and are compared with the well known results for thin circular arc sections illustrated in the Structural Data Sheet 00.06.04.

The cross sections considered are bounded by two circular arcs *ADB* and *ACB* as shown in Fig. 1. The inner arc *ADB* has its centre *O* on the circumference of

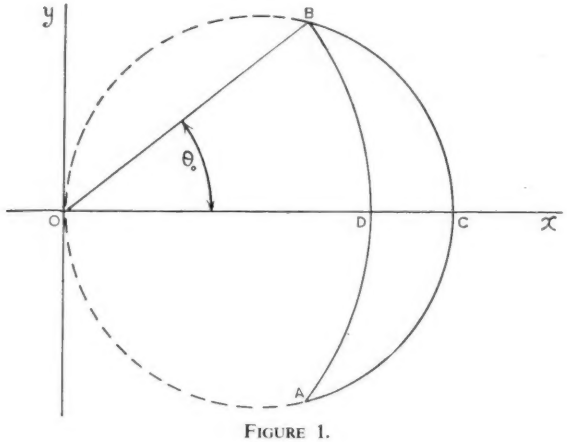

FIGURE 1.

the circle of which the outer arc *ACB* forms a part. For these sections the torsion function has been given by Larmor[3] as

$$\phi_3 + i\psi_3 = i\left[z - \frac{a^2}{z} + \frac{a^2}{2}\right]$$

where z is the complex co-ordinate measured from the origin O, $OB=a$ and $OC=2$ units. The notation for the torsion functions ϕ_3 and ψ_3 used here is that given by Stevenson[4] and his notation is also employed elsewhere in this note.

The determination of the location of the centre of shear is most conveniently carried out in this example by evaluating its distance from O, so that the expressions given by Jacobs and Duncan for the distance of the centre of shear from the centroid of the section require some generalisation. Stevenson has given the distance of the shear centre from a chosen origin in a form which reduces for a section with a single axis of symmetry to

$$f_0 = \frac{L_2}{2I'} + \frac{\nu}{1+\nu}\left(\frac{M_1 - hM_3}{2I'}\right)$$

where L_2, M_1 and M_3 are moment integrals depending on the torsion and flexure functions, I' is the moment of inertia for bending about the axis of symmetry, h the distance of the centroid from the origin and ν is Poissons ratio.

The three moment integrals, although given by Stevenson in forms involving flexure functions in addition to the torsion functions, are readily transformed, using Green's theorem, into integrals involving only ϕ_3 and ψ_3. They are then conveniently expressed in terms of contour integrals and take the following forms:—

$$L_2 = -\frac{1}{3}\oint\left(\phi_3 + \frac{xy}{3}\right)\frac{\partial y^3}{\partial n}\,ds$$

$$M_1 = \oint x^3\frac{\partial}{\partial n}\left(\frac{x^2}{8} - \frac{\psi_3}{3}\right)ds$$

$$M_3 = \oint \psi_3\frac{\partial}{\partial n}\left(\frac{x^2+y^2}{4} - \psi_3\right)ds.$$

It should be noted that these forms require a knowledge of the values of ϕ_3 on the boundary only, since ψ_3 is here equal to $\frac{1}{2}(x^2+y^2)$ and $\frac{\partial\psi}{\partial n} = -\frac{\partial\phi}{\partial s}$. This data is also

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sufficient for determining the shear stress on the surface and is frequently more readily calculated than the variation of ϕ_3 or ψ_3 throughout the section.

The integrals are evaluated for the cross sections considered in terms of the parameter $\theta_0 = \cos^{-1} a/2$ but as the resulting expressions are lengthy only numerical results are presented here. Table I gives the values of the constant term and the term dependent on Poissons ratio in the equation for f_0, equation (2), and also the distance of the centroid h from the origin O for a range of values of θ_0.

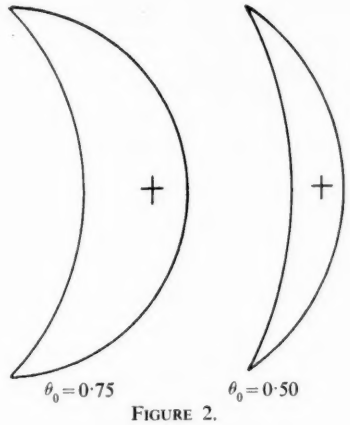

FIGURE 2.

The influence of Poissons ratio on the position of the shear centre is seen to be small throughout and this tends to confirm Jacob's conclusion that for a cambered aerofoil it is unimportant in the calculation of the component of the displacement of the shear centre from the centroid in a direction perpendicular to the chord line. Fig. 2 shows the cross sections for $\theta_0 = 0{\cdot}75$ and $0{\cdot}50$ together with the location of the shear centres.

The final column in the table gives the position of the centre of shear k, again measured from O, for a thin

TABLE I

θ_0	$L_2/2l'$	$(M_1 - hM_3)/2l'$	h	k
0·25	1·982	0·0001	1·951	1·988
0·50	1·922	0·0012	1·811	1·951
0·75	1·806	0·0061	1·604	1·889
1·00	1·604	0·0181	1·366	—
1·25	1·298	0·0300	1·145	—
1·50	1·020	0·0067	1·009	—

circular arc extending from A to B and cutting the axis midway between C and D. A comparison shows that this approximation, neglecting the thickness of the section, over-estimates the displacement of the shear centre from the centroid.

The results presented here, although limited to sections having a particular relation between camber and thickness, provide some guide to the location of the centre of shear for circular arc profiles. The solution of the general problem for sections bounded by any two circular arcs which would, of course, enable variations of thickness and camber to be considered separately, has not been attempted as it involves much lengthier computation due to the more complicated form of the torsion function.

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The Use of Glass Cloth/Resin Moulded Components in the Laboratory

by

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THE PURPOSE of this note is to call attention to the convenience of glass cloth/polyester resin laminates as a means of constructing certain parts of experimental apparatus, such as small ducts or nozzles.

The advantages of the material are that it is strong, light in weight, easily worked in that heat and pressure are not required, and a high degree of accuracy and surface finish are easily achieved. For the purposes considered here, convenience in fabrication is the main consideration, since it is easier to shape the outside of a suitable male mould rather than the inside of a small duct.

Such considerations led to its use for the construction of a small (2 in. dia. working section) supersonic induction wind tunnel, intended for testing a model injector of a type similar to that proposed for a 12 in. × 12 in. tunnel. To provide various Mach Numbers at entry to the injector, a number of interchangeable supersonic

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FIGURE 1. Contraction, nozzles, mixing sections and diffuser for 2 in. diameter supersonic wind tunnel.

nozzles were required. Their external finish was obviously quite unimportant, whereas to machine the insides to the required degree of accuracy would have presented a difficult problem.

Each mould was made from well-seasoned teak, turned on a lathe to fit a sheet metal template. To facilitate extraction from the cured laminate, a joint was provided at the throat of each mould and the two parts were located and held together by a central screwed rod.

FIGURE 2. Typical nozzle and wooden mould, with parallel mixing section in foreground.

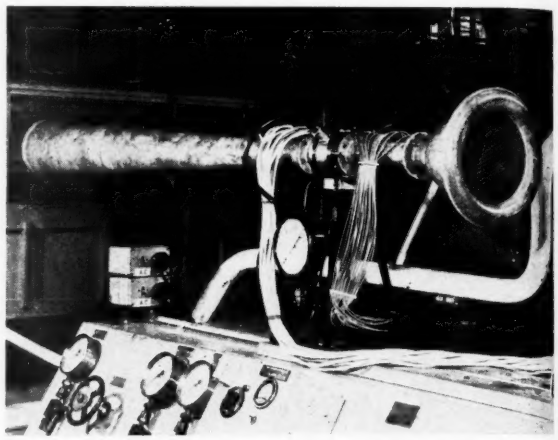

FIGURE 3. Two-inch diameter supersonic tunnel for injector tests.

By facing the joint surfaces before assembly on to the rod and then turning the mould as one unit, no ridge was produced in the finished nozzle. The grain of the wood was filled with beeswax, domestic floor polish being used as a parting agent to prevent the resin sticking to the mould. Since the moulds were used immediately, no trouble was experienced due to shrinkage of the wood. Marco resin 28c and 0·009 in. thick woven glass cloth were applied to the mould in the usual way,[1] using four layers of cloth. When the resin was completely cured the nozzle was trimmed to length and the mould removed. Previously prepared flanges were then fitted and attached by a fillet of cloth and resin. Where static pressure tappings were required, several strips of woven glass tape were bonded to the nozzle and short lengths of steel tube were stuck into the tube with resin. When the resin had set, holes were drilled through the tubes into the nozzle wall.

Some skill is required to produce satisfactory mouldings, particularly in laying up the laminate.

In mouldings such as these nozzles, which had only small amounts of taper, difficulty was initially experienced in extracting the moulds, but after a few failures little further difficulty was experienced.

Other parts of the tunnel were constructed in a similar fashion to that already described (Figs. 1 and 2). For the diffuser, the mould was of plaster, on a rough structure of wooden discs and longitudinal strips. The contraction mould was of solid teak and the short parallel mixing lengths were made on collapsible moulds. Fig. 3 shows the assembled tunnel.

The experience gained with this tunnel indicates that this technique provides a very convenient means of constructing small ducts and similar components, and no doubt other applications will readily suggest themselves.

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Wind Tunnel Balance Design— The Simultaneous Measurement of Forces and Moments

by

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(Blackburn and General Aircraft Co. Ltd.)

AN ELECTRO-MECHANICAL METHOD of simultaneous component separation is suggested as an alternative to mechanical systems. Based on the commonly used weighbeam, employing a motor driven leadscrew, poise weight, selsyn repeater circuit and counter, component separation is proposed by means of the selsyn differential circuit.

The use of the selsyn motor as a direct or differential telemeter mechanism is well known[1], and as such, has many industrial applications. Such use, applied to the aerodynamic balance, offers the advantage of avoiding many of the difficulties associated with design and in particular, the construction of a mechanically independent and simultaneous measuring instrument.

Separation is obtained by including the selsyn differential motor in the selsyn repeater circuit as found in some automatic or semi-automatic balances. The circuit so formed takes the place of a mechanical system of separation and effectively simplifies the design. Unlike the more complex mechanical systems, *see* Ref. 2, in which component separation is made internally prior to weighbeam response, the above electrical circuit completes the process externally to the balance mechanism. This means that some of the weighbeams will make a double or complex measurement which is well illustrated elsewhere[3]. Such a response is not new to balance design and by suitably wiring the differential circuits, simultaneous measurement is obtained by a summation or difference of the appropriate quantities during transmission to the particular component counter.

Figure 1 will be recognised as one instance of a two-dimensional arrangement exhibiting simple and complex weighbeam measurement. It will be seen when weighbeams *A* and *B* are in equilibrium, *A* measures

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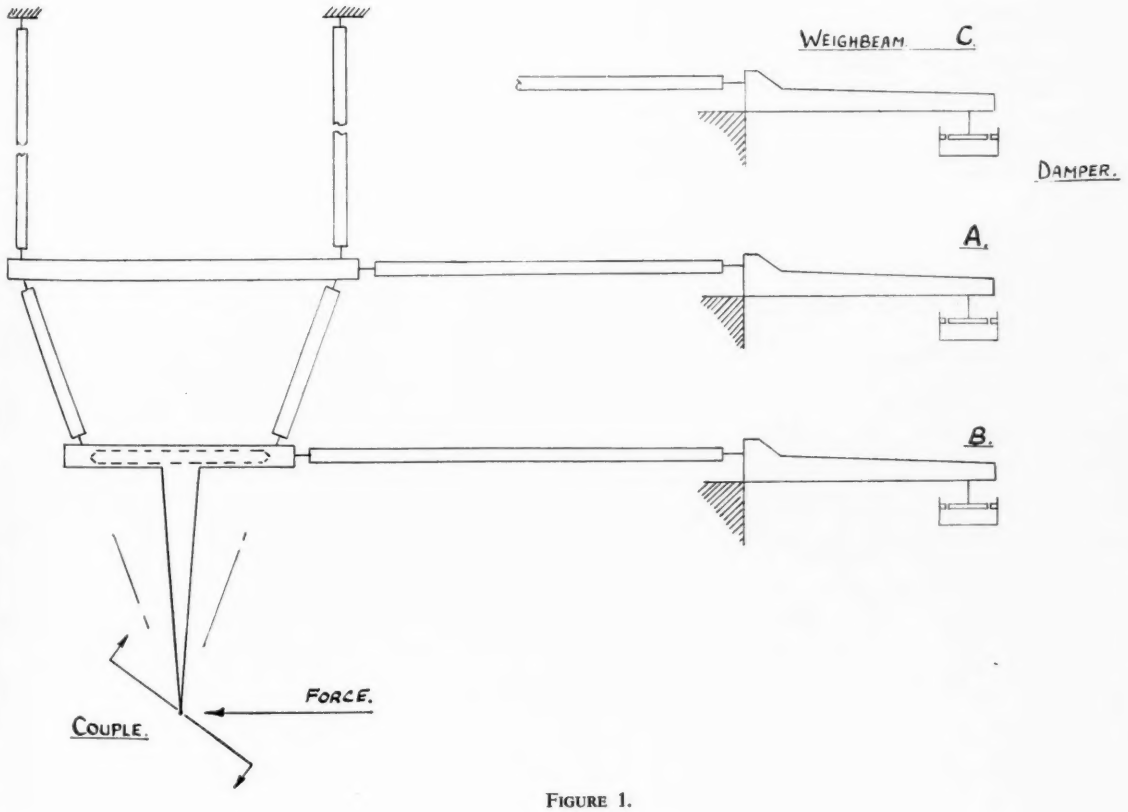
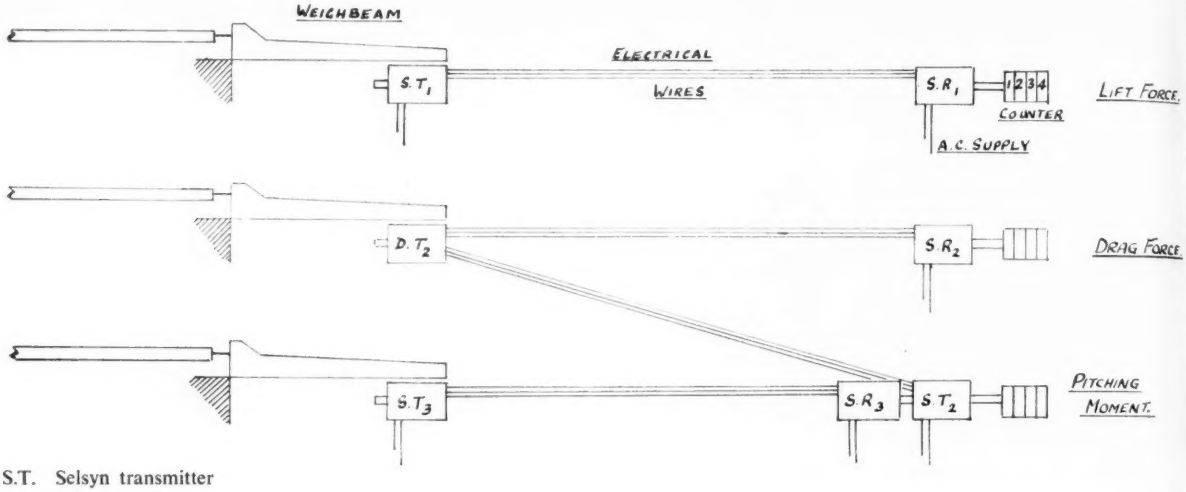


FIGURE 1.



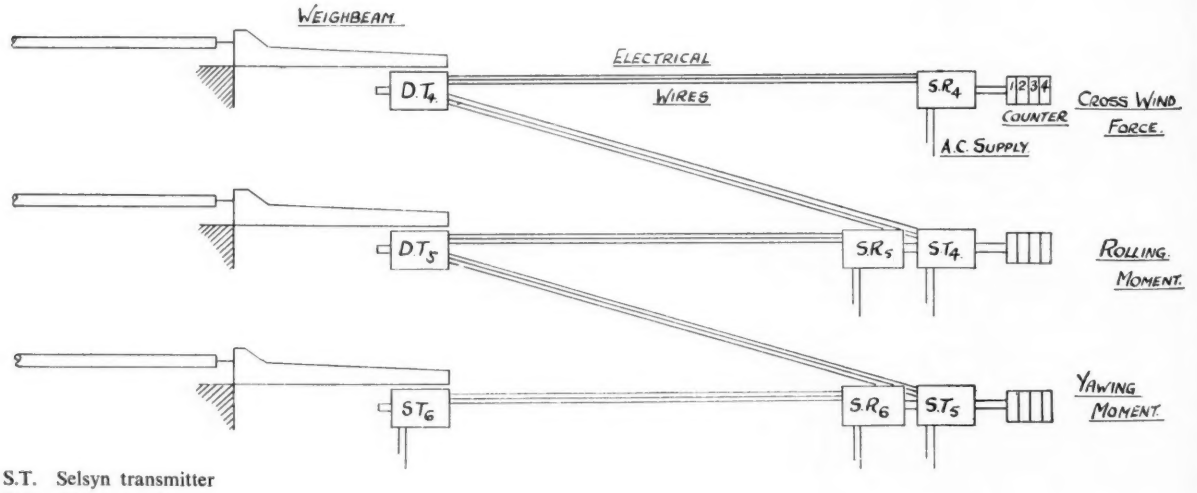
S.T. Selsyn transmitter
S.R. Selsyn receiver
D.T. Differential Selsyn (independently fed)

FIGURE 2. Longitudinal weighbeam counter circuit.

the force through the "pyramid" intersection and similarly, A and B together measure the moment. Hence, when a moment occurs as a result of a force acting about this intersection, A measures not only the force, but also the equivalent couple force arising (about the intersection) from this moment. Then, if as in this case (although this is in no sense a restriction) equal turns of the transmitter selsyns of A and B represent equal weighbeam measurements, *i.e.* equal differences of poise weight moments, the couple measurement by A will be effectively neutralised by an electrical correction from the selsyn of B and the direct force measurement only is transmitted to the counter associated with A, while the moment measurement is transmitted to the counter associated with B. Fig. 2 gives this differential circuit.

The transverse system of weighbeams and electrical circuits, respond in precisely the same manner and the electrical circuit is given in Fig. 3. The resulting simultaneous measurement of all components is as follows:

Counter reading	*Weighbeam measurements*
Lift force	C
Drag force	$A-B$
Cross wind force	$D-(E-F)$
Pitching moment	BxC_1
Rolling moment	$(E-F)xC_2$
Yawing moment	FxC_3



S.T. Selsyn transmitter
S.R. Selsyn receiver
D.T. Differential Selsyn (independently fed)

FIGURE 3. Transverse weighbeam counter circuit.

The constants C_1 to C_3 may either be incorporated into the balance calibration, or conveniently represented by two small gears situated between the counter and receiver selsyn. The latter arrangement has, from experience, repeated accurately to well within one count in a range of ten thousand.

As already mentioned, there are balances which either solve this problem in a more complex manner, or alternatively, are unable to give simultaneous measurement of all six components. The present proposal or one of the variants, offers, it would seem, a simple and attractive basis for the design of a wind tunnel balance.

It can also be incorporated in an existing six-component balance requiring separation of forces and moments, although it is inevitable that in a case which does not include six separate weighbeams the necessary additional units would have to be included.

The foregoing method of simultaneous separation has not, so far as is known, been adapted to the design of a balance although its application as a servo-mechanism is fairly common.

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N.B.—Selsyn repeater motor
B.T.H. SM 1406.
Selsyn differential motor.
B.T.H. S 1406 Dl.

Definition of Specific Impulse

by

F. W. THORNE

I WISH to support S. W. Greenwood's plea (December 1953 JOURNAL) for defining "specific impulse" as Thrust/Mass flow of propellants.

Apparently some engineers are now using Thrust/weight flow of propellants as the definition of specific impulse, but it would appear that this innovation is merely due to inability to distinguish between mass and weight. The system used at the Royal Naval College, Greenwich, of using the capital letter to denote weight or force (*e.g.* Lb.) and the lower case to represent mass (*e.g.* lb.) is a very convenient way of distinguishing between the two.

We would then write the specific impulse as, say,

$$215\left(\frac{\text{Lb.}}{\text{lb./sec.}}\right).$$

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Also, since a pound weight is equal to a pound mass multiplied by g, we have

$$\text{Lb.} = \text{lb.} \times g = \text{lb.} \times 32{\cdot}18 \text{ ft./sec.}^2$$

i.e. $$\left[\frac{\text{Lb. sec.}^2}{\text{lb.} \times 32{\cdot}18 \text{ ft.}}\right] \text{ is unity.}$$

Also the specific impulse may be expressed as a velocity, the conversion being as follows:—

$$\text{Specific impulse} = 215 \frac{\text{Lb. sec.}}{\text{lb.}} \times \left[\frac{\text{lb.} \times 32{\cdot}18 \text{ ft.}}{\text{Lb. sec.}^2}\right]$$

$$= 6{,}919 \text{ ft./sec.},$$

which is sometimes called the "effective gas velocity."

ERRATUM

In the Technical Note (December 1953 JOURNAL) "Definition of Specific Impulse" by S. W. Greenwood, p. 819, the phrase "fast-pound-second" should obviously be "foot-pound-second."

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Reviews

MODERN DEVELOPMENTS IN FLUID DYNAMICS—HIGH SPEED FLOW. *Oxford: at the Clarenden Press 1953. 2 Vols. 875 pp. 26 plates. 288 figs. 84s. net.*

The original "Modern Developments in Fluid Dynamics" appeared in 1938; it was prepared under the auspices of the Fluid Motion Panel (now Sub-Committee) of the A.R.C. and edited by S. Goldstein. This book has acquired an international reputation and is very frequently quoted but its subject was restricted to the motion of *incompressible* fluids. The volumes now under review are, on the contrary, entirely concerned with *compressible* fluids and, in fact, almost wholly with gases. Like their predecessors, they have been composed under the aegis of the Fluid Motion Sub-Committee of the A.R.C. The heavy task of editing has been ably done by L. Howarth with assistance from H. B. Squire and the late C. N. H. Lock. In all, seventeen authors, each an expert in the subject of his contribution, have collaborated in the writing. Since, further, each contributor had the advantage of discussions with the members of the Fluid Motion Sub-Committee, there can be no doubt that this is a book of quite exceptional authority. The phrase "High Speed Flow" in the title means, of course, that the speed of flow is not small in relation to the velocity of sound in the fluid, *i.e.* the Mach number of the flow is not so small that the influence of the compressibility of the fluid is negligible.

The first and introductory chapter is contributed by the principal Editor and contains a general survey of the subject. Some new technical terms are introduced here for the first time. Thus, a field of flow is said to be *homentropic* when the entropy of the fluid per unit mass is constant throughout the field and the word *isentropic* is used to describe curves or surfaces on which the entropy per unit mass is constant. Likewise, a field of flow is called *homenergic* when there is no loss or gain of the total energy in any part of it, *i.e.* when the quantity $(\Omega+I+\frac{1}{2}q^2)$ is constant, where Ω is the potential function of the body forces, I is the enthalpy per unit mass and q is the resultant velocity of the fluid. Flow across a shock wave is homenergic but not homentropic. Chapter II, also by the Editor, discusses the equations of motion of compressible viscous and inviscid fluids, thermodynamic principles and some general deductions from these. There is also a brief reference to the influence of the molecular structure of the flowing gas, but the reader is referred to the book, "Mathematical Theory of Non-uniform Gases" by Chapman and Cowling for a full discussion.

In Chapter III R. E. Meyer deals very clearly and thoroughly with the *method of characteristics*, while W. G. Bickley contributes Chapter V which contains a number of exact solutions of the equations of steady homentropic flow of an inviscid gas, such as the "Prandtl-Meyer expansion" and the solution by Taylor and Maccoll of the problem of supersonic flow past a cone. The theory of "one-dimensional flow," *i.e.* flow in a single narrow streamtube, is discussed by O. A. Saunders in Chapter VI, and M. J. Lighthill treats the *hodograph transformation* and its applications in Chapter VII. Approximate methods, which are of great value in the practical applications of theory, are expounded by G. N. Ward in Chapter VIII, while the theory of unsteady flow, which has important applications to the theory of the aerodynamic derivatives of flutter and of stability and control, is treated by G. Temple in Chapter IX. A. D. Young contributes a chapter of 100 pages on boundary layers and the remaining chapter of Volume I is concerned with shock waves (C. R. Illingworth) and blast waves (G. J. Kynch).

Volume II is almost wholly concerned with experimental methods and results, with the exception of the treatise on heat transfer (Chapter XIV, of almost 100 pages) by H. B. Squire. D. W. Holder, D. C. Macphail and J. S. Thompson are the authors of the very extensive chapter on experimental methods, which includes discussions of wind tunnels and of the correction of the results obtained from tests in tunnels, ancillary instruments and the visualisation and photography of fluid motion. A summary of knowledge about flow past aerofoils and cylinders is presented by W. A. Mair and J. A. Beavan in Chapter XII, while in Chapter XIII W. F. Cope discusses flow past bodies of revolution and the technique of tests on projectiles.

The foregoing brief analysis of the contents of this book shows that it has a very wide scope as well as being authoritative. It is not, however, all-comprehensive and is, in fact, almost wholly concerned with pure aerodynamics on the theoretical and experimental sides. The book is not suitable for the beginner since a good deal is, quite properly, taken as known, but it will be of great value to all advanced students of aerodynamics and to the very numerous persons who apply this science. The Editor and the team of authors are to be warmly congratulated on the success of their onerous undertaking, while the Publisher must be thanked for the excellent printing and production of the volumes which are offered at a price which is very moderate in relation to the value received.—W. J. DUNCAN.

STATISTICS FOR TECHNOLOGISTS. *C. G. Paradine and B. H. P. Rivett. English Universities Press Ltd. 288 pp. with index. Figs. and Tables. 25s. net.*

This book sets out to steer a middle course between the treacherous possibilities of an account either of the analysis of statistics or of the numerical application of the most useful results. Quite generally, it is at least arguable that to kick against the pricks of the fact of specialisation is useless, and that no good purpose is gained by attempting to write a book for several kinds of specialists. Certainly, success in such an attempt is rare but this particular book is one of these rarities. That is not to say that the book—described in a sub-title as an introduction—is the most suitable for all kinds of students beginning to learn the subject. A pure mathematician would probably be repelled by what he would regard as a sordid mass of numerical detail about lamps, wires and tolerances; in any case the book, while making the valid point that many basic results are obtainable by a variety of methods, omits, for example, the theory of generating functions. But the virtue of the book is that this mathematician, and other similar specialists, will come to use the book to supplement and extend knowledge already gained.

The first five chapters follow the usual and almost inevitable pattern of establishing the basic ideas of frequency distributions and probability; a third of the book

is thus accounted for. The variety and interest of the copious examples is an excellent feature of this part. Chapters VI, VII and VIII are on Small Samples, Quality Control and Sampling Inspection Schemes. These are no mere sops to the factory engineer but full accounts of what are extremely important applications of statistical theory. Next come the Theory of Errors and The Method of Least Squares and it is an interesting comment on the authors' outlook that these two chapters do not precede Chapters VI-VIII. Correlations and Variance are treated extensively and suitably for workers in widely differing fields, and the last chapter is on the Principle of Maximum Likelihood.

The whole book is written in an admirably lucid style, and it does not hesitate to describe qualitatively more difficult ideas, which though they lie outside the scope of the book, are often pertinent. It is highly to be recommended.—B. THWAITES.

PETROLEUM AND PERFORMANCE. *E. M. Goodger. Butterworths Scientific Publications. 295 pp. Diagrams. 32s. 6d. net.*

"Fuels and Engines" might have been a better title for this book than its present one, which hardly does justice to the material it contains. It is true that the preface explains that the objective is to illustrate the interrelationship of petroleum fuels and the performance of internal combustion engines, but actually the text goes much further into the engine problems than the emphasis in the title on petroleum would suggest. Furthermore, although the book treats the subject matter in a general manner, it is notable that aero-engine experience is used extensively to illustrate the points. It is, in fact, a book with as much interest, if not more, for the aeronautical engineer than for the fuel technologist or chemist.

The book falls into two main parts. The first covers crude oil and its products, chiefly from the viewpoint of the oil industry. This is an aspect of which many engine designers and operators are only vaguely aware and it can be recommended on this score alone. The ground covered includes the winning of the crude oil, the production of fuels, the types of hydrocarbon, their properties and testing. This section, as already indicated, is relatively short, and the second part is much more extensive. It covers sufficient engine theory for a proper appreciation of the following chapters which are devoted to the principles and applications of combustion, fuel rating, mixture behaviour, fuel spray atomisation and engine applications. While this part should be of most value to propulsion engineers, it should also prove useful to the non-specialists and others who wish to have a general understanding of the subject.

The book is intended to fill a gap between the popular type of handbook and the detailed work of reference, aiming at the undergraduate student level. Generally, the author has succeeded admirably in maintaining this level and he has presented the subject matter in the concise and clear manner which is the hall mark of a good text book. In one or two places, however, he has permitted himself to rise above the level, as in discussing some of the theoretical aspects of combustion. Occasionally, too, he has taken for granted that the reader knows the meaning of abbreviations, but it is not everybody who will recognise immediately that I.P. 59/49, for example, means Institute of Petroleum Test No. 59, dated 1949. Other points include such things as changes in type for symbols from capitals to small letters or to italics. These minor criticisms do not detract from the value of the book, which is recommended to all who want sound technical information on the subject in an easily absorbed form.—A. D. BAXTER.

LUBRICANT TESTING. *E. G. Ellis. Scientific Publications (Great Britain) 1953. 232 pp. Illustrated. 37s. 6d. net.*

This monograph presents recent developments in the testing of lubricants in such a manner as to provide a satisfactory text book to chemists and laboratory testers and at the same time an authoritative and readable treatise for engineers and others interested in lubrication. The ten chapters may be grouped under three main headings, (1) Fundamental Properties and Flow Problems; (2) Composition, and (3) Behaviour.

Fundamental properties are dealt with in the first three chapters in which the physical properties of liquids are discussed and the various methods of viscosity determination are explained. Sufficient theoretical background is given to provide a basis for discussion of the flow properties of Newtonian and non-Newtonian fluids. The next four chapters are devoted to tests of composition, such as pour point, volatility, carbon residue, oxidation and so on, with references to the relevant I.P. and A.S.T.M. method.

The final three chapters deal with Friction and Lubrication, Functional Tests and Engine Testing. These constitute the most important section of the book.

Chapter VIII on Friction and Lubrication is essentially a discussion of machines for testing Extreme Pressure lubricants and the more basic principles of the Timken, Shell Four Ball, Falex, S.A.E. and Almen E.P. tester are discussed and illustrated. The virtues and weaknesses of each machine are presented without any attempt to prejudice the reader in favour of any particular machine. Functional tests are discussed in Chapter IX and include Anti-friction Bearing Rigs, Torque Measurements, Shearing Tests, Hub and Gear Tests, Interpretation of Results and Water Resistances.

Chapter X deals with Engine Testing and an account is given of the American (C.R.C.) and English (Sunbury, Shell Ricardo and BLOGRO) test engines developed in recent years for lubricant testing, together with a brief account of methods used for the testing of aircraft engine oils. Actual engine details are not given, but the conditions under which the engines are operated are described so that the relative merits of each test can be assessed.

There are six appendices, the first four dealing with tests for greases (S.K.F. testing machine, Hoffman running test, British Timken water resistance and heat tests for lime soaps and a Tentative Cone Resistance Test) and the last two with the viscosity of water and other substances.

Anticipating the adoption of a new value for the viscosity of water at 20°C. a table is included giving the factors by which any new standard viscosity at 20°C. must be multiplied to give the dynamic viscosity of water at any other temperature. A new figure was adopted by the Bureau of Standards and A.S.T.M. Committee D-2 in 1953, and conversion tables based on the new value are given in "A.S.T.M. Special Technical Publication No. 43A."

The text is eminently readable and is well illustrated and provided with an adequate index. Selected bibliographies are given at the end of each chapter.—F. MORTON (Birmingham University).

BASIC MECHANICS OF FLUIDS. *Hunter Rouse and J. W. Howe. John Wiley, New York. Chapman & Hall, London 1953. 245 pp. 145 Figures. 36s. net.*

This work is intended as a textbook for undergraduates and to those engineers who require an elementary knowledge of fluid mechanics. In the United Kingdom, however, its standard will barely reach that required by the Higher National Certificate Examination. It will probably be of most interest to those engineering students, specialising in hydraulics, who require a more descriptive account of

certain aspects of fluid motion than is available in the present literature.

The book is divided into ten chapters. The subjects covered include fluid statics, kinematics and dynamics, gravity and viscosity effects, resistance to bodies in motion and the flow of fluids in pipes, lift and its application to propellers and turbo-machinery, and compressibility effects. An appendix gives the physical properties of common fluids. The book is very well furnished with worked examples and problems with answers. The authors have deliberately kept the standard of mathematics well within the grasp of the average engineering student, even to the extent of avoiding a single use of the partial differential coefficient. An important omission is the lack of a list of symbols.

Although the book is well presented, easy to read, and is readily understandable, it is not without its faults. It suffers from a lack of attention to the description of fundamentals. For instance the discussion on rotational and irrotational flow by illustrative methods alone, and the neglect of such quantities as circulation and vorticity, can hardly lead to the student obtaining a strong grasp of the importance and application of such terms. In addition the inadequate treatment of the formation of lift on an aerofoil and the omission of sections on induced drag, downwash and cascade effects deprive the reader of a knowledge of those fundamentals which are so important in the application of the principles of fluid motion to practical problems. It is surprising that as little as three pages are devoted to the theory of dimensions and that no mention is made of the units of physical quantities commonly used in fluid mechanics. Thus, although the slug is often used as the unit of mass in worked examples in the text, no definition of this quantity is given.

The authors have attempted to excuse themselves of these defects, by stating in the Preface that they have preferred rather to deal with as wide a range of subjects as possible, giving each a minimum of attention, than to neglect any essential phase of the subject. If therefore they had made frequent references to other published work, dealing more fully with those aspects of the subject for which space alone had prevented adequate treatment, a sufficient answer to the foregoing criticisms would have been given. As it stands, the lack of a single reference to other published data makes recommendation of this book difficult. In addition the price is on the high side, although this is presumably due to American publication.—G. M. LILLEY (College of Aeronautics).

THE ATOMISATION OF LIQUID FUELS. *Prof. E. Giffen and Dr. A. Muraszew. Chapman & Hall, London 1953. 246 pp. Diagrams. 36s. net.*

The efficient combustion of liquid fuels depends upon proper atomisation and proper air mixing, and it is natural that atomisation has been the subject of very wide study.

In this book the authors have collected together useful information from many sources, as well as the fruits of original work; drawing both on theory and experience, they set out to explain the various factors which contribute to or affect the process of atomisation. Each aspect is introduced by a consideration of the natural laws involved, and then illuminated by a presentation of practical results and illustrations. One can imagine quite a number of eager purchasers of this book being somewhat disappointed, not with what it contains so richly, but rather with the absence of matter which they might have expected to find in it. However, the title provides some justification for the omissions, and it must presumably be left for a companion volume to cover the field of "atomisers" as distinct from "atomisation."

There are firm grounds for the view that atomisation should be separated into two categories, even although the end result is the same in each. The first category would deal exclusively with plain hole or penetrative atomisation, of intermittent or jerk type, as almost universally applied in solid injection engines, and the second would deal with swirl atomisation, of the rapid dispersion type as used in any continuous flow process whether it be combustion, spray painting, fruit spraying or powder production. In the present book the authors tend rather to ride the two horses together, and to some extent this makes for confusion since at times one wonders which is the mount of the moment, although the identity of the favourite is rarely in doubt.

The present reviewer feels that the two categories might with advantage have been treated in separate sections, with perhaps a subsequent chapter summarising their points of identity and difference.

Anyone new to the subject will gain the impression that whatever the type of atomiser, the process of atomisation is never complete at the atomiser itself, but proceeds to completion subsequently and progressively due to the action of the surrounding air on the droplets. The inclusion of Fig. I-4 (Lane and Edwards, Porton), which shows so beautifully the break-up of a drop in an air stream, sows this impression, and it is repeated several times in the text. Unfortunately, no idea is given of the initial drop size in Fig. I-4, nor of the air stream velocity. In fact these values are 2·2 mm. (*i.e.* 2,200 microns) and 80 ft./sec., and what happens to droplets of this order of size is no criterion of what happens to droplets in a spray. The relatively much smaller droplets in a spray are very stable and resistant to distortion and break-up, and require quite fierce velocities of air suitably directed to cause their disruption. Furthermore, with swirl type atomisers it is found that the spray produced when discharging into a near-vacuum is of the same order of fineness as when spraying into atmospheric or even denser media. The inference is that in such cases the disintegration process occurs directly from and is completed at the atomiser, due to the energy of the fluid, and the various velocity components to which it is subjected in flow.

Attention may be called to a few minor printing discrepancies. On page 61 Fig. II-14 shows as the abscissa $\log \log (100/R)$, whereas the text above quotes $\log \log (1/R)$. On page 102, in the symbols list, the suffixes 1 and 2 in relation to D are stated to refer to the circumferences of swirl chamber and orifice respectively, whereas presumably diameters are meant. In Fig. VI-8, on page 140, the first figure on the abscissa should read 10, and not 0, as shown.

Disregarding these small points, the book is of excellent standard.

The authors are to be congratulated on the very painstaking and valuable work they have done in making such an exhaustive survey of the literature, and bringing together the pith of a diversity of publications for the reader's benefit.—J. R. JOYCE (Thornton Research Centre).

THE DIMENSIONING OF ENGINEERING DRAWINGS. *W. Abbott. Blackie & Sons Ltd., London 1953. 186 pp. 333 Figures. 10s. 6d. net.*

Dr. Abbott is the author of a number of well known books on Engineering Drawing and this present volume is a worthy addition to the series.

In the preface Dr. Abbott writes "This book deals with the fundamental principles which apply to the dimension-

ing of drawings for engineering components in their finished state, in the manufacture of which interchangeability is a paramount requirement. It is concerned with the distribution of tolerances previously decided upon, not with the determination of these tolerances . . . "

It must be admitted that in a large number of cases the dimensioning of drawings has been an extremely haphazard affair and an intelligent appreciation of the principles underlying correct dimensioning technique is absolutely essential. Many books on machine drawing have been published from time to time and the British Standards Institution have issued their Specification No. 308 in an effort to arrive at uniformity in drawing office practice.

Dr. Abbott's book may be said to be an elaboration of British Standard 308 and illustrates the applications of the recommendations contained in the Specification.

The importance of interchangeability is appreciated in every sphere of the aircraft industry and any means whereby the standard can be improved is worthy of real study. I believe that this book will do much to clear up a number of difficulties which beset not only students but more established members of drawing office staffs.

The first two chapters are devoted to the general problem, the choice of dimensions and ranges of sizes. Chapters Three to Seven contain much useful information on the application of tolerances to dimensioning; the treatment of limits as applied to holes, shafts, points and lines being particularly well covered. Chapter Seven will be of special interest to aeronautical engineers dealing as it does with the positioning of holes in thin material.

Chapters Eight and Nine dealing with Size and Form, and Mating Components respectively give adequate coverage to the application of tolerances to machined parts including those possessing relative movement.

Chapter Ten is devoted to a review of a number of standard systems specifying tolerances for shafts and holes, these include British Standard 164, the I.S.A. 25 originally designed by the International Federation of the National Standardizing Association, the American Standards Association A.S.A. B4a and the Newell System. The author reviews each system, giving illustrated examples and underlining the urgency for devising an International system.

Chapter Eleven covers certain aspects of Surface Texture including suggestions for indicating the requirements on individual drawings.

The concluding chapter is entitled " The Theory of Probability and its Impact on Dimensioning " and in it Dr. Abbott deals with the possibility of easing the tolerance values when the manufacturing processes are under control and the degree of accuracy of a large number of components can be predicted.

There is very little, if any, criticism which can be levelled at this book. The subject is treated in a clear and easily understood manner and the many examples are well illustrated and presented. The cost at half a guinea brings it within the reach of the engineering apprentice in whose reference library it should certainly find a place.—E.J.M.

FEATHERED WINGS. *Anthony Jack. Methuen. 131 pp. 15 plates. 15s. net.*

The ramifications of science continue to spread and the quantity of knowledge in any one branch to increase. As a consequence few men can make themselves experts in more than one branch and those who write about more than one subject are to be commended. The author of " Feathered Wings " has succeeded in providing a good A.B.C. on the subject of bird flight; more knowledge is slowly being accumulated about it, but what might be called the X.Y.Z. cannot be written until research has explained many unknown factors. Such factors include the complicated airflow over flexible surfaces at the low Reynolds numbers of flight, in which region there is, at present, very little scientific interest for the aerodynamicist who has been drawn to the more immediate problems of transonic and supersonic flight. If birds made supersonic bangs and shook our houses, they would provide an urgent stimulus for research. As they don't, we must be content with the gradual collection of information. Here, the author has made a valuable contribution from his own observations in several parts of the world. More are needed and there is room for close observations in this country, for example, how exactly does a starling counter successfully the up current sideways on when he passes from leeward to the windward of the roof ridge of a house, or what precisely does a flycatcher do when he suddenly spots and catches a gnat just before he is going to alight on a favourite perch. The latter flight (as also the hovering of a humming bird) has a similarity to the hovering flight of a helicopter.

Turning to the details of the book we find that the chapters on elementary aerodynamics, anatomy, meteorology and navigation support those on flapping flight, on gliding flight, on the effect of the wind on the bird and on the manœuvres that birds execute in the air. The book also has excellent photographs. In some cases, however, a more modern presentation of the scientific side would easily have been possible if experts in the respective subjects (*e.g.* aerodynamics and meteorology) had been consulted. It is very difficult to be consistently clear in explaining matters dependent on the motion of the air relative to a moving wing which both changes its shape and flexes. In this last connection the terms " pronation " and " supination " lead to difficulties which can be avoided by the use of the simpler aerodynamic terms defined later in the book. We hope that in another edition the author will have something to say about Graham's classic work on the bastard (slotted) wing and on Matthews' recent experiments on bird navigation. The figures for the normal flight speeds of various birds are in accordance with recent measurements although no mention is made of Penrose (and other pilots) contributions to this knowledge. There are so many excellent accounts of the author's own observations that perhaps a word of caution is necessary. Rarely do two observers seeing the same or similar things give the same interpretation. Two examples might suffice: (1) Almost every bird eases his landing by a last well-timed flap and this may be the predominant part of the manœuvre and (2) tumbler pigeons may first stall at a large angle of incidence of the wings and then do a quick roll and not turn " head over heels."—J.L.N.

THE WINGED LIFE: A PORTRAIT OF ANTOINE DE SAINT-EXUPÉRY, POET AND AIRMAN. *Richard Rumbold and Lady Margaret Stewart. George Weidenfeld and Nicolson, 1953. Index. 224 pp. 16s. net.*

Several biographies of Saint-Exupéry have already been written and published in France; this new one is the first to appear in England, written by two collaborators whose enthusiasm is such that they flew all over France, seeking acquaintances, friends and relations of " Saint-Ex." in order to obtain a first-hand impression of him.

Failing direct personal knowledge—that is the best way to do it; yet it is no light task to attempt the portrayal of a man one has never seen, relying on the assessment of hearsay to re-mould a pre-conceived image evoked by his prose. Though at times Richard Rumbold and Lady

Margaret Stewart seem to venerate too greatly the importance of psycho-analytical interpretation, and occasionally offer contradictory impressions within a few paragraphs, nevertheless they succeed in revealing much of the background of Saint-Exupéry's life, and by the frequent interpolation of synopsis and extracts from his books produce the effect of a factual representation of his life. But with a writer of such insight and humanity as Saint-Exupéry one wants more than that. The biographer of a man who has made so distinctive a mark in the world needs to discover the spiritual growth as well as the soil from which it sprang.

The story of childhood days may faintly indicate the man; an account of adventures as pioneer airline pilot may more clearly suggest his calibre; unsettled, empty months, desparation and vagrant jobs may foreshadow the exile and heart-searching of early war years—but no bare chronicle of such events can evoke the swift and vivid impress of any single chapter of his books. The essence of the man is in all he wrote; a Frenchman first, a flying man next, and then an author of exquisite sensibility whose romantic writing is tempered with an authenticity sprung from deep experience of beauty and peril. In all that matters Saint-Exupéry was his own biographer. What one would like to see is a book written by Richard Rumbold in the style of his own introduction "a mystique of humanity in the solitude and perspective of the starry heavens."—HARALD J. PENROSE.

AVIATION FACTS AND FIGURES 1953. *R. Modley and T. J. Cawley, Editors. Lincoln Press, Washington, 1953. 224 pp. Index.*

Perhaps the editors' foreword's first paragraph is sufficient commendation for this book: "This volume is not a work of original research. It merely brings together from hundreds of sources all the available facts which have been considered of importance or interest."

The word "merely" is, strangely in an American, a miracle of understatement since the book is a mass of tables of the sort that one spends hours digging out of separate journals. For instance, table 2-2 is "Value of Aircraft and Parts Produced 1914-1953"; table 7-6 "Hours Flown by Utility Aircraft 1931-1951"; table 8-4 "Exports of Civil Aircraft 1948-1952" (according to type). There is an excellent index and the book is divided into Chapters with such headings as Production, Labour, Finance, and Military Aviation.

The pity of it is that the figures are nearly all American; one chapter deals with Foreign Aviation Data.

STUDENT AND PRIVATE PILOT'S HANDBOOK. *H. H. Edwards. Pitman, London, 1953. 100 pp. 12s. 6d. net.*

This book is mainly for students who wish to qualify for a Private Pilot's Licence, but it will be found to be most useful for the guidance of any student pilot. In a practical way, it provides information on flying rules and regulations, on navigation and on meteorology, sufficient for the written examination, and all "under one roof."

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Reports

AERODYNAMICS

Boundary Layer

An approximate solution of the compressible laminar boundary layer on a flat plate. R. J. Monaghan. R. & M. 2760 (*November* 1949, *published* 1953).—(1.1.1).

The turbulent boundary layer in compressible flow. W. F. Cope. R. & M. 2840 (*November* 1943, *published* 1953).

The flow of a compressible gas past a flat plate is investigated for a turbulent boundary layer. The local and mean skin-friction coefficients are calculated for both power and log laws of velocity distribution. The calculations show a considerable reduction of both coefficients with increasing M. In the course of the analysis assumptions have been made whose accuracy is not proven, though they are consistent with those made in incompressible gas dynamics.—(1.1.3).

Compressible Flow

Curves for estimating the wave drag of some bodies of revolution, based on exact and approximate theories. L. E. Fraenkel. A.R.C. Current Paper 136 (*August* 1952, *published* 1953).

Curves are presented for estimating the wave drag, at zero incidence, of forebodies and afterbodies having straight and parabolic profiles. The afterbodies are assumed to lie behind an infinitely long cylindrical body. The curves are based on a limited number of exact and second-order solutions which have been generalised by appealing to the supersonic-hypersonic similarity law and to slender body and quasi-cylinder solutions.—(1.2.3).

Fluid Dynamics

Spectrum of turbulence in a contracting stream. H. S. Ribner and M. Tucker. N.A.C.A. Report 1113 (1953).

Spectrum concepts are employed to study the selective effect of a stream contraction on longitudinal and lateral turbulent velocity fluctuations. By consideration of the effect of stream contraction on a single plane wave, the effect on spectrum and correlation tensors of the turbulence is determined. Weak turbulence and an inviscid fluid are postulated; compressibility of mean flow only is taken into account. For axi-symmetric contraction and isotropic initial turbulence, explicit results are obtained.—(1.4).

Analogy between mass and heat transfer with turbulent flow. E. E. Callaghan. N.A.C.A. Technical Note 3045 (*October* 1953).

An analysis of combined heat and mass transfer from a flat plate has been made in terms of Prandtl's simplified physical concept of the turbulent boundary layer.—(1.4).

Internal Flow

Design of a right-angled bend with constant velocities at the walls. A. S. Thom. A.R.C. Current Paper 135 (*February* 1952, *published* 1953).

In designing a corner in a two-dimensional duct it is possible, by the insertion of an aerofoil, to maintain the same constant velocity on the outer and inner walls. It is, however, necessary to shape these walls to suit the conditions. The present paper gives a method whereby the aerofoil and walls can be designed. Two examples are given.—(1.5.1).

Performance Estimation

The loss in climb performance, relative to the optimum, arising from the use of a practical climb technique. K. J. Lush. R. & M. 2756 (*August* 1949, *published* 1953).

A practical climb technique is considered which is defined by a fixed relation between equivalent air speed (or Mach number) and pressure altitude, and a rough estimate made of the loss in performance involved in using such a technique with a turbine jet aircraft over a range of air temperature, engine speed, thrust, or aircraft weight. An approximate method of calculating a suitable relation is given in an Appendix.—(1.7).

Stability and Control

Courbes de réponse en fréquence des avions. J. Carpentier et J. F. Vernet. Publications Scientifiques et Techniques du Ministère de L'Air, France, No. 286 (1953).—(1.8).

Wings and Aerofoils

The theory of aerofoils with hinged flaps in two-dimensional compressible flow. F/Lt. L. C. Woods. A.R.C. Current Paper 138 (*August* 1952, *published* 1953).

This paper presents a theory of two-dimensional controls in compressible flow which is almost as simple to apply as Glauert's theory and is as accurate as the method of Goldstein and Preston. An example given by Goldstein and Preston is treated by the author's method to illustrate this point.—(1.10.1.1).

Observations on a thin cambered aerofoil beyond the critical Mach number. E. W. E. Rogers. R. & M. 2432 (*July* 1950, *published* 1953).

In the course of surface pressure measurements and wake traverses on an aerofoil section of 10 per cent. thickness/chord ratio, tested at high subsonic speeds in the 20×8 in. (50·8 x 20·3 cm) High-Speed Wind Tunnel of the National Physical Laboratory, it was discovered that at a particular incidence (3·7 deg.) an extensive region of supersonic velocity ($M = 1{\cdot}15$) existed without the formation of a well-defined shock-wave or a rise of drag. The drag coefficient in fact decreased markedly as the Mach number was raised from a low value, and this was accompanied by a rearward movement on the upper surface of the position of boundary-layer transition corresponding to a favourable change of the surface pressure gradient. The transition positions measured with the "china-clay" method are compared with those estimated from the observed drag coefficients. Direct-shadow photographs illustrate the development of the shock-wave pattern.—(1.10.2.1).

Two-dimensional aerofoil design in compressible flow. L. C. Woods. R. & M. 2731 (*November* 1949, *published* 1953).

This paper deals with the following two-dimensional problem:—"The design of an aerofoil to give a specified velocity against chord curve at a given free stream Mach number." A "relaxation" method is adopted, based on the differential equations for incompressible and compressible flow. The method is developed for a symmetrical aerofoil at zero incidence, but the modifications necessary for the more general case are indicated. A worked example is given, from which some idea of the accuracy of the method can be gained.—(1.10.1.1).

Low-speed measurements of the pressure distribution at the surface of a swept-back wing. V. M. Falkner and Doris E. Lehrian. R. & M. 2741 (*November* 1949, *published* 1953).

Low-speed measurements of the pressure distribution have been made at selected stations on a swept-back wing with and without body. The wing was of 45 deg. sweepback, with a sharp discontinuity at the centre-section, and of aspect ratio 3 with uniform chord. The aerofoil section was chosen to be suitable for work at low Reynolds number, and the wing plan to be of the maximum utility for comparison of observed and calculated pressure distribution. The work is the first part of a programme designed to give results of the greatest assistance to the development of mathematical methods, and the model was of exceptionally clean design to avoid extraneous effects.—(1.10.2.2).

NOTE:—*The figures in parentheses at the end of each Summary are for office use only.*

Wind-tunnel tests on the prevention of boundary-layer separation by distributed suction at the rear of a thick aerofoil (NPL 153). N. Gregory, R. C. Pankhurst and W. S. Walker. R. & M. 2788 (*October* 1950, *published* 1953).

Tests of a preliminary nature have been carried out on a 33 per cent. thick symmetrical aerofoil (NPL 153) with suction through a porous surface from 0·80 chord to the trailing edge, which was rounded and fitted with a Thwaites flap. The distributed suction was found to prevent separation and to reduce the wake drag to zero. The overall effective drag (including an allowance for the power required for the suction) was reduced slightly, but still remains fairly high. No hysteresis was observed in the change of drag with suction quantity.—(1.10.2.1).

Note on aerodynamic camber. H. C. Garner. R. & M. 2820 (*April* 1950, *published* 1953).

This has been written at the suggestion of the Chairman of the Stability and Control Sub-Committee. It is intended to explain the theoretical significance of camber derivatives, and to assess the various available methods of making experimental measurements with particular reference to the use of a curved-flow tunnel.—(1.10).

TESTING AND INSTRUMENTS

Note on the use of the three-dimensional shock wave recorder for studying interference in a supersonic wind tunnel. A. O. Ormerod. R. & M. 2798 (*December* 1950, *published* 1953).

A description is given of the three-dimensional shock-wave recorder which has been used to investigate wind-tunnel interference on a sting-mounted wing having 50 deg. of sweepback. Diagrams of the shock-wave patterns round the wing are given from which it can be inferred that the outboard portion of the particular wing tested suffers interference from the tunnel walls at $M = 1{\cdot}4$. At the higher Mach numbers the model behaves effectively as if it were in free air. In order to use the three-dimensional shock-wave recorder, the wind-tunnel working-section requires a window whose length is at least three times the tunnel width and which extends equal distances ahead of and behind the model. This is a very serious drawback to the general use of the method. The analysis of the photographic records is straightforward, though rather tedious.—(1.12).

Design of a rate-of-rotation recorder. S. J. Murphy and S. H. G. Connock. N.A.E. Canada, Laboratory Report LR-68 (July, 1953).

This report describes a recorder of the continuous-trace type designed to record simultaneously rates of rotation of an aeroplane about three mutually perpendicular axes. It includes a brief review of some possible methods of measuring rates of rotation and also a theoretical study of the behaviour of such recording devices when the parameter to be recorded has a frequency of the same order as that of the recording elements. Results of laboratory dynamic tests are given.—(1.12).

Counting methods and equipment for mean-value measurements in turbulence research. H. W. Liepmann and M. S. Robinson. N.A.C.A. Technical Note 3037 (*October* 1953).

Methods of measuring the probability distributions and mean values of random functions as encountered in turbulence research were studied. Applications to the measurement of probability distributions of the axial velocity fluctuation and its derivative in isotropic turbulence are shown.—(1.12).

High-frequency pressure indicators for aerodynamic problems. Y. T. Li. N.A.C.A. Technical Note 3042 (*November* 1953).

Three different types of pressure indicators are discussed. Each of these indicators has a unique feature, but all are designed with an attempt to combine both high-frequency response and high resolving power into one instrument.—(1.12).

HYDRODYNAMICS

A theoretical approach to the design of hydrofoils. C. H. E. Warren. R. & M. 2836 (*September* 1946, *published* 1953).

An investigation has been made into the application of the theory of thin sections to the design of hydrofoils having high cavitation speeds. Consideration is given to both symmetrical sections, which themselves are suitable for struts, and camber-lines, which, when used with the symmetrical sections, lead to cambered sections which are suitable for lifting surfaces. In all the aim has been to keep the peak local velocities to a minimum, and the sections developed differ from "low-drag" aerofoil sections mainly in that, being hydrofoils, the sections have sharp leading edges.—(17.1).

Water performance of a four-engined flying boat with step fairings of length 3, 6 *and* 9 *times the step depth. G. J. Evans, A. G. Smith, R. A. Shaw and W. Morris. R. & M.* 2868 (*April* 1941, *published* 1953).

Tests were made to investigate the hydrodynamic qualities of the Sunderland flying boat, when fitted with step fairings of mean gradient 1:3, 1:6 and 1:9. Attitude and acceleration measurements were made during take-offs, landings and constant-speed taxying runs. Water pressure measurements were made at various stations over the forebody and afterbody hull bottoms with and without the step fairings of 1:6 and 1:9 ratio.—(17.2).

INSTRUMENTS AND EQUIPMENT

A direct reading thermistor thermometer for aircraft use. G. M. Wright. N.A.E. Canada, Laboratory Report LR-65 (June 1953).

This report describes an aircraft thermometer of the following type: — Direct-reading unbalanced bridge without amplification, using two thermistors as sensing elements. Stable bridge voltage is supplied from a dynamotor via a two-stage glow tube regulator.—(18.4).

An aircraft icing-rate meter. G. M. Wright. N.A.E. Canada Laboratory Report LR-66 (June 1953).

An instrument is described which gives rate of aircraft icing as indicated by the duration of the "off" period of any "off-on" type of icing detector. During each off-period, one of two identical low-loss condensers is discharging through a suitable resistance while the other, without leakage resistance, is displaying its voltage via a simple electronic voltmeter. These functions are interchanged at each on-period, during which interval the measuring condenser is also recharged. The instrument is stabilised and operates directly from 25- to 30-volt direct current.—(18.4).

MATERIALS

Application of silver chloride in investigations of elasto-plastic states of stress. L. E. Goodman and J. G. Sutherland. N.A.C.A. Technical Note 3043 (*November* 1953).

Quantitative relationships between the state of elastic or plastic stress in a specimen and the observed relative retardation and extinction angle were developed from a general theory of stress birefringence, according to a stress-dependent hypothesis. The relationships were verified experimentally by measurements on single-crystal specimens of silver chloride tested in simple tension in the elastic and plastic stress ranges. Silver chloride appears to be a suitable medium for photoelastic studies of effects of plastic yielding on the state of stress in a crystalline specimen.—(21.6.1 × 33.3.2).

MECHANICAL ENGINEERING

Calcul statistique des systèmes asservis. M. J. Pelegrin. Publications Scientifiques et Techniques du Ministère de L'Air, France, No. 285 (1953).—(23.2.3).

METEOROLOGY

Circulation and distortion of liquid drops falling through a viscous medium. P. Savic. N.R.C. Canada, Report No. MT-22 (July 1953).

Existing theories of circulation in drops moving through a viscous medium are examined and found to be at variance with observation on water drops moving in castor oil. It is concluded that the suppression of circulation in small drops is due to a surface active layer, the extent of which is governed by the balance between interfacial tension and the integral of viscous surface shear.—(24).

Supersaturation in the spontaneous formation of nuclei in water vapour. A. Sander and G. Damkohler. N.A.C.A. Technical Memorandum 1368 (*November* 1953).

The supersaturation of water vapour required for spontaneous formation of nuclei was measured in the temperature range between +35° and −75°C. The influence of the presence of ions on the condensation process was found to disappear and a break in the critical supersaturation as a function of temperature curve was found at −62°C. A modified form of the Volmer and the Becker-Doring equations for rate of nucleus formation is presented and compared with the experimental data.—(24).

POWER PLANTS

The performance of some typical turbo-jet engine exhaust systems, with particular reference to the effects of swirl. P. F. Ashwood and P. J. Fletcher. A.R.C. Current Paper 130 (*December* 1951, *published* 1953).

A description is given of tests made to determine the effect of swirl on the performance of a quarter-scale model of a typical turbo-jet engine exhaust system and propelling nozzle. The losses in the system were derived from direct measurement of the thrust.—(27.1).

The calculated performance of ethyl alcohol-water mixtures as rocket fuels with liquid oxygen. A. B. P. Beeton. R. & M. 2816 (*March* 1948, *published* 1953).

Specific impulses and combustion temperatures have been calculated for rocket propellants consisting of liquid oxygen and ethyl alcohol-water mixtures. This system appears to have a number of advantages compared with the corresponding liquid oxygen and petrol system.—(27.3).

RESEARCH

Multiple-jet white-smoke generators. C. Salter. R. & M. 2657 (*March* 1950, *published* 1953).

Descriptions are given of equipment devised for the generation of fairly large quantities of an optically dense white smoke and special attention has been paid to the need for delivering this through long ducts or against an appreciable back-pressure. The smoke consists of very small particles of condensed paraffin vapour and is obtained by directing jets of cool air on to high speed jets of the vapour issuing from very small orifices.—(31.1).

The 9×3 in. induced-flow high-speed wind tunnel at the National Physical Laboratory. D. W. Holder and R. J. North. R. & M. 2781 (*June* 1949, *published* 1953).

A 9×3 in. high-speed wind tunnel driven by a compressed-air injector has been built in the Aerodynamics Division of the National Physical Laboratory. The tunnel operates at roughly atmospheric stagnation pressure and has so far been used to give Mach numbers up to 1·8. The general arrangement of the tunnel and the preliminary calibration, which is generally satisfactory, are described.—(31.2.1).

Development of intermittent high-speed wind tunnel installations and testing techniques. J. Lukasiewicz. N.A.E. Canada, Laboratory Report LR-75 (*July* 1953).

Two types of intermittent wind tunnel drives, the pressure storage drive (with atmospheric exhaust) and the vacuum storage drive (with atmospheric inlet) are examined and found to match well the tunnel pressure ratio-mass flow characteristics over a wide Mach number range (0 to 4). The design of components of intermittent wind tunnel installations, their operation and instrumentation are then considered in some detail. Relative merits of continuous and intermittent installations are discussed.—(31.2.1).

SCIENCE—GENERAL

Contribution a l'étude de la courbe de resonance d'un quartz. J. Coulon. Publications Scientifiques et Techniques du Ministère de L'Air, France, No. N.T. 47 (1953).—(32.2.3).

Étude du mécanisme de la pulverisation des solutions électrolytiques par l'étincelle anodique. P. Barret. Publications Scientifiques et Techniques du Ministère de L'Air, France, No. N.T. 48 (1953).—(32.2.1).

STRUCTURES

Loads

The vibrations of a swept wing. N. S. Heaps. A.R.C. Current Paper 141 (1953).

The vibrations of a swept wing with ribs parallel to the direction of flight are considered theoretically. The couplings of torsion and flexure due to the skewness of the ribs and the building-in of the root section are investigated.—(33.1).

Natural frequencies and modes of a model delta aircraft. D. R. Gaukroger. R. & M. 2762 (*June* 1950, *published* 1953).

Resonance tests on a model delta wing are described. Consideration is given to the effect of inertia distribution on the first three normal symmetric modes of vibration. The mean centre of gravity position, fuselage pitching moment of inertia and wing inertia axis have been independently varied, and the effect of concentrated tip masses has been examined. Results are given which are intended as a general guide in flutter calculations.—(33.1.2).

On the analytical determination of the normal modes and frequencies of swept cantilever vibrations. A. H. Hall, H. F. L. Pinkney and Helen A. Tulloch. Laboratory Report LR-76, N.A.E. Canada (*July* 1953).

A procedure for calculating the normal modes and frequencies of swept cantilever plates is outlined, and is illustrated with a numerical example. Comparison of the theoretical frequencies is made for plates of 0, 30, 45 and 60 degrees sweep, and of the modes for 30, 45 and 60 degrees sweep.—(33.1.2).

Theory and Analysis

See also Thermodynamics—Heat Transfer

Four studies in the theory of stress concentration. H. L. Cox. R. & M. 2704 (*January* 1950), *published* 1953). (*Monograph*).

The four studies considered are:—

Part I—The effect of holes on the strength of materials under complex stress systems.

Part II—Stress concentration due to holes and grooves other than elliptical in form.

Part III—The effect of surface irregularities on fatigue strength.

Part IV—Stress concentration in twisted shafts.—(33.2).

The elastic stability of sandwich plates. Sqn. Ldr. J. H. Hunter-Tod. R. & M. 2778 (*March* 1949, *published* 1953).

This paper treats the elastic stability of supported rectangular plates of sandwich construction with isotropic and aeolotropic fillings under compression and shear loading. Formulae are developed for critical stresses for flat and curved panels in compression and flat panels in shear for the buckling of the whole panel, also for the wrinkling or local failure of the faces of flat panels in compression. It is established that for a wide range of conditions the critical stress for panels buckling in compression is independent of the form of the filling providing it is symmetrical about the normal; of the elastic constants of the filling only the transverse shear is of concern. As a result a simple extension of the equivalent plate theory of greatly improved accuracy is developed enabling the use of equations treating the plate as a whole.—(33.2.4).

Summary of theoretical work done on the stability of thin plates 1939 *to* 1946. *D. M. A. Leggett. R. & M.* 2784 (*September* 1950, *published* 1953).—(33.2.4).

Buckling of right-angled isosceles triangular plate in combined compression and shear. (*Perpendicular edges clamped, hypotenuse simply supported.*) *W. H. Wittrick. A.R.L. Australia. Report SM.*211. (*June* 1953.)

The problem considered is that of the buckling of a right-angled isosceles triangular plate clamped along its two perpendicular edges and simply supported along the hypotenuse. The applied load is a combination of uniform shear along the perpendicular edges, and uniform compression in all directions. An interaction curve between the shearing and compressive buckling stresses is derived.—(33.2.1).

*The uniform torsion of a perfectly plastic circular ring. W. Freiberger. A.R.L. Australia Report SM.*213 (*July* 1953).

This report continues the discussion of the torsion of a circular ring, begun in Report SM.122 for an elastic medium, by giving the solution when the material of the ring is perfectly plastic, *i.e.* when it yields under constant stress. This is an approximation to the problem of helical springs of circular cross-section and small aspect ratio.—(33.2).

*The thin clamped parallelogram plate under uniform normal pressure. F. H. Dorman. A.R.L. Australia. Report SM.*214 (*August* 1953).

The deflections and bending moments for a thin clamped parallelogram plate under uniform normal pressure were determined by a Ritz method using a double cosine series in oblique co-ordinates. A numerical check of the results was obtained by comparing the strain energy of the deformed plate with the work done by the external forces. The computations were made with 10 figures and the check led to an agreement to 6 or more figures, which was taken to be satisfactory.—(33.2.4).

A simplified theory of swept wing deformation. A. H. Hall. N.A.E., Canada. Report 19 (1953).

A simplified theory is presented for determination of displacements along the locus of section shear centres within the root triangle of a swept wing, and formulae are derived which permit straightforward calculation of the outboard influence coefficient for any loading condition. The theory is developed on the premise that in any mode of deformation, the effect of alteration in the direction of principal strains can be represented by a complementary shearing action along the locus of section shear centres, and that the distribution of this shearing action can be approximated by a simple polynomial with constant coefficients to be evaluated by the principle of least work.—(33.2.3).

Comparative fatigue tests with 24 *S-T Alclad riveted and bonded stiffened panels. J. H. Rondeel, R. Kruithof and F. J. Plantema. N.L.L. Holland. Report S.*416.

The purpose of the investigation was to compare the fatigue strengths of bonded and riveted flat sheet-stringer panels of identical construction, except for the sheet-stringer joints. The results of fatigue tests on panels stiffened with angle section stringers and top-hat stringers are given.—(33.2.4).

Stresses in a two-bay noncircular cylinder under transverse loads. G. E. Griffith. N.A.C.A. Report 1097 (1952).

A method, taking into account the effects of flexibility and based on a general eighth-order differential equation, is presented for finding the stresses in a two-bay, non-circular cylinder the cross section of which can be composed of circular arcs. Numerical examples are given for two cases of ring flexibility for a cylinder of doubly symmetrical (essentially elliptic) cross section, subjected to concentrated radial, moment, and tangential loads. The results parallel those already obtained for shells with circular rings.—(33.2).

Charts relating the compressive buckling stress of longitudinally supported plates to the effective deflectional and rotational stiffness of the supports. Roger A. Anderson and Joseph W. Semonian. N.A.C.A. T.N. 2987. (*August* 1953.)

The stability of a plate under edge compressive stress is analysed in terms of the deflectional and rotational stiffnesses of one or more longitudinal lines of support between the plate side edges. The results are presented in the form of charts which make possible the determination of the compressive buckling stress of plates supported by members whose stiffness may or may not be defined by elementary beam bending and twisting theory, but yet whose effective restraint is amenable to evaluation. The deflectional and rotational restraint provided by longitudinal stiffeners and full-depth webs is discussed, and numerical examples illustrate the application of the charts to the design of wing structures.—(33.2.1).

Column strength of H-sections and square tubes in postbuckling range of component plates. P. P. Bijlaard and G. P. Fisher. N.A.C.A. T.N. 2994. (*August* 1953.)

The column buckling stress in the range where the component plates have buckled is calculated by the method of split rigidities. For the elastic range simple formulas are derived which express the column buckling stress in terms of the Euler buckling stress of the column, the plate or local buckling stress, and the local buckling stress for a higher mode of buckling. For the plastic range a Johnson parabola is proposed which in the buckling-stress-slenderness diagram is tangent to the curve for the elastic column buckling stress in the post-buckling range.—(33.2.4).

WEIGHT ANALYSIS AND CONTROL

*Structural efficiency of multi-web wings. J. Solvey. A.R.L. Australia. Report SM.*212 (*July* 1953).

This report deals with an extension of the work done on the single-web wing to the multi-web wing. A numerical investigation was carried out on a certain number of wings, which has revealed certain trends in the relations between the minimum weight of the wing, the number of webs and certain parameters of the aircraft. These trends can serve as a guide to the designer in the preliminary stages of the design, when the basic proportions of the structure have to be decided upon.—(33.4.1).

THERMODYNAMICS

Kinetic temperature of wet surfaces. J. K. Hardy. R. & M. 2830 (*September* 1945, *published* 1953).

A method is given for calculating the temperature of a surface wetted either by a pure liquid, such as water, or by a mixture, such as alcohol and water. The method is applied to the problem of protecting, by alcohol, propellers and the induction system of the engine against ice.—(34.4 × 29.3).

Recherches sur les limites d'inflammabilité de vapeurs de composés solides. L'inflammation électrique des mélanges de vapeurs de naphtalene et d'anhydride phtalique avec l'air. L. Dolle. Publications Scientifiques et Techniques du Ministère de L'Air, France, No. 287 (1953).—(34.1.1).

HEAT TRANSFER

Air cooling methods for gas turbine combustion systems. F. J. Bayley. A.R.C. Current Paper 133 (*August* 1951, *published* 1953).

This paper presents an account of the whole of the work which has been done at the National Gas Turbine Establishment on the problem of air-cooling gas turbine combustion systems. Each of the different methods of wall cooling is discussed separately and the theory and mechanism of the cooling process is developed from first principles.—(34.3 × 1.9).

The measurement of heat transfer and skin friction at supersonic speeds. Part III. Measurements of overall heat transfer and of the associated boundary layers on a flat plate at $M_1 = 2{\cdot}43$. *R. J. Monaghan and J. R. Cooke. A.R.C. Current Paper* 139 (*December* 1951, *published* 1953).

Results are given of overall heat transfer measurements and of pitot and thermocouple traverses of the associated boundary layers on a flat plate at $M_1 = 2{\cdot}43$.—(34.3).

The measurement of heat transfer and skin friction at supersonic speeds. Part IV. Tests on a flat plate at $M = 2{\cdot}82$. *R. J. Monaghan and J. R. Cooke. A.R.C. Current Paper* 140 (*June* 1952, *published* 1953).

This note gives the results of overall heat transfer and boundary layer measurements made on a flat plate in a 5 in. square supersonic wind tunnel operating at $M = 2{\cdot}82$ under atmospheric stagnation pressure conditions. The tests were made to extend the range of results previously obtained at $M = 2{\cdot}43$ and used the same experimental equipment.—(34.3).

Temperatures, thermal stress, and shock in heat-generating plates of constant conductivity and of conductivity that varies linearly with temperature. S. V. Manson. N.A.C.A. T.N. 2988. (*July* 1953.)

Working formulas are presented for the steady-state temperatures and thermal stress in heat-generating infinite plates of constant conductivity, and of conductivity that decreases linearly with temperature as the temperature increases, for the case in which the heat is generated uniformly throughout the plate thickness and both faces of the plate are equally cooled. A criterion is indicated for determining the surface cooling conditions under which the thermal shocks at the surface and midplane will be smaller than, equal to, or greater than, the steady-state thermal stresses at those planes.—(34.3.3 × 33.2.2).

APPOINTMENTS

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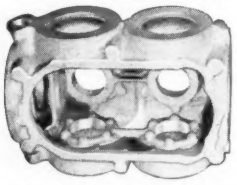

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